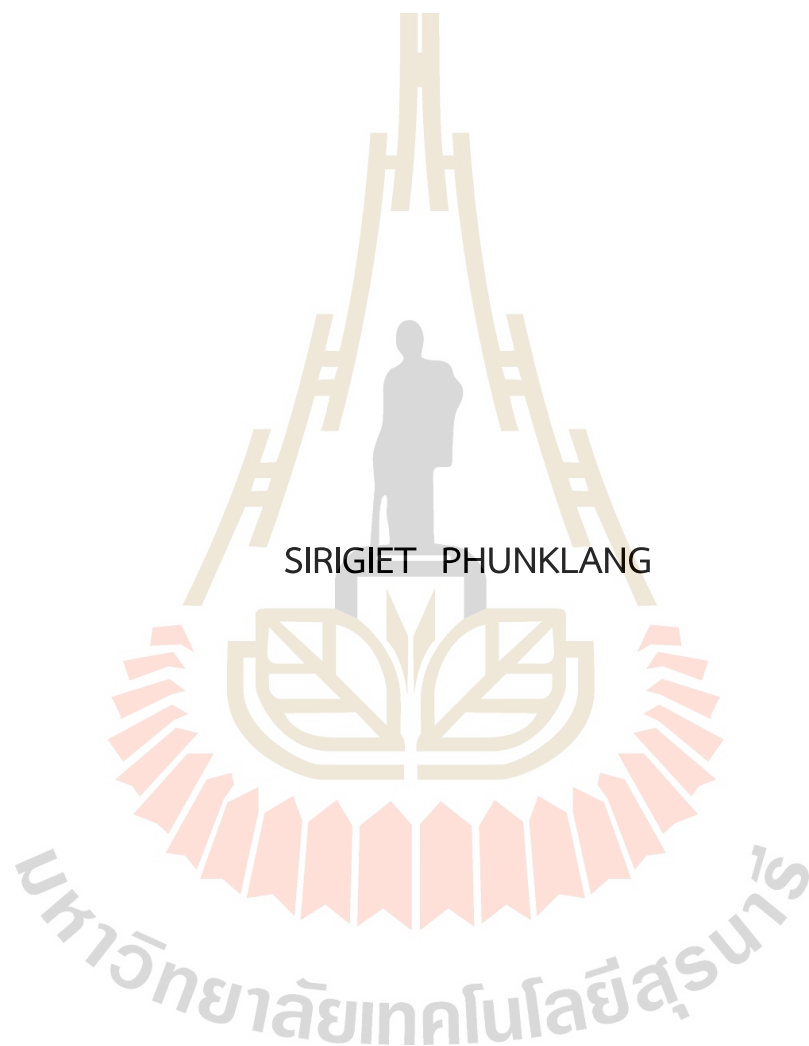


THE DESIGN OF NANOPLASMONIC ANTENNA USING PANDA-RING CIRCUIT



SIRIGIET PHUNKLANG

A Thesis Submitted in Partial Fulfillment of the Requirements for the
Degree of Doctor of Philosophy in Telecommunication
and Computer Engineering
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การออกแบบสายอากาศนาโนพลาสมอนิกโดยใช้วงจรรูปตัวจริง



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THE DESIGN OF NANOPLASMONIC ANTENNA USING PANDA-RING CIRCUIT

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

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ความก้าวหน้าของระบบสื่อสารความถี่สูงและเชิงแสงได้กระตุ้นการพัฒนาโครงสร้างการแผ่พลังงานระดับนาโนที่รองรับอัตราการส่งข้อมูลสูงภายใต้ข้อจำกัดด้านขนาดและการสูญเสียของวัสดุสายอากาศนาโนพลาสมอนิกจึงเป็นแนวทางที่มีศักยภาพ โดยอาศัย Surface Plasmon Polaritons (SPPs) เพื่อกักเก็บและแผ่สนามแม่เหล็กไฟฟ้าได้อย่างมีประสิทธิภาพต่ำกว่าขีดจำกัดการเลี้ยวเบน วิทยานิพนธ์นี้นำเสนอการออกแบบสายอากาศนาโนพลาสมอนิกที่ผสานวงจรแพนด้าริงกับตะแกรงทองคำ โดยใช้ Whispering Gallery Modes (WGMs) ภายในแพนด้าริงเป็นแหล่งกระตุ้นหลัก การจำลอง WGM ดำเนินการด้วยวิธี FDTD (OptiFDTD) และถ่ายโอนสัญญาณกระตุ้นไปยัง CST Studio Suite เพื่อวิเคราะห์สมบัติการแผ่พลังงานแบบเต็มคลื่น ภายใต้สัญญาณกระตุ้นเดียวกันได้เปรียบเทียบโครงสร้างสามรูปแบบ ได้แก่ (1) ทรงกระบอกซิลิคอน (2) ตะแกรงทองคำ และ (3) โครงสร้างแพนด้าริงแบบผสมที่นำเสนอ การวิเคราะห์สนามไกลดำเนินการที่ความถี่ 193.5 THz ผลการจำลองเชิงตัวเลขแสดงให้เห็นว่า โครงสร้างซิลิคอนเพียงอย่างเดียวให้ค่าอัตราขยายของสายอากาศ เท่ากับ 4.12 dBi (ประสิทธิภาพการแผ่พลังงาน -0.3786 dB, ประสิทธิภาพรวม -3.101 dB) ขณะที่โครงสร้างตะแกรงทองคำเพียงอย่างเดียวให้ค่าอัตราขยายของสายอากาศเพียง -0.539 dBi (ประสิทธิภาพการแผ่พลังงาน -6.764 dB, ประสิทธิภาพรวม -7.826 dB) ในทางตรงกันข้าม โครงสร้างแพนด้าริงแบบผสมที่นำเสนอให้ค่าอัตราขยายของสายอากาศสูงถึง 8.05 dBi พร้อมกับประสิทธิภาพการแผ่พลังงาน -1.20 dB และประสิทธิภาพรวม -2.20 dB ซึ่งคิดเป็นการเพิ่มกำลังขยายประมาณ 3.9 dB เมื่อเทียบกับซิลิคอนเพียงอย่างเดียว และมากกว่า 8.5 dB เมื่อเทียบกับตะแกรงทองคำเพียงอย่างเดียว

ผลดังกล่าวยืนยันว่าการผสมผสานตะแกรงทองคำบนทรงกระบอกซิลิคอนเข้ากับแพนด้าริง ช่วยเสริมการคับปลิงเชิงพลาสมอนิกและเพิ่มประสิทธิภาพการแปลงพลังงานจากสนามเรโซแนนซ์ที่ถูกกักเก็บ (WGM) ไปสู่การแผ่คลื่นได้อย่างมีประสิทธิภาพ โครงสร้างที่นำเสนอนี้จึงทำหน้าที่ได้ทั้งเป็นสายส่งสัญญาณเชิงแสงและสายอากาศนาโนพลาสมอนิกที่เหมาะสมสำหรับระบบสื่อสารไร้สายเชิงแสงในอนาคต

สาขาวิชาวิศวกรรมโทรคมนาคม
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ลายมือชื่อนักศึกษา.....
ลายมือชื่ออาจารย์ที่ปรึกษา.....
ลายมือชื่ออาจารย์ที่ปรึกษาร่วม.....

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Rapid progress in high-frequency and optical communication systems has driven the development of nanoscale radiating structures capable of supporting ultra-high data rates under strict size and material-loss constraints. Plasmonic nanoantennas offer a promising approach by utilizing surface plasmon polaritons (SPPs) to achieve strong electromagnetic confinement and efficient radiation beyond the diffraction limit. This thesis proposes a hybrid plasmonic nanoantenna that integrates a Panda-ring resonator with a gold grating. Whispering Gallery Modes (WGMs) generated within the Panda-ring serve as the primary excitation source. The WGM response is simulated using the Finite-Difference Time-Domain (FDTD) method in OptiFDTD, and the extracted time-domain signal is transferred to CST Studio Suite for full-wave far-field analysis at 193.5 THz. Under identical WGM excitation, three configurations are evaluated: (1) silicon cylinder only, (2) gold grating only, and (3) the proposed hybrid Panda-ring structure. The silicon-only configuration achieves a realized gain of 4.12 dBi (radiation efficiency = -0.3786 dB, total efficiency = -3.101 dB), while the gold-only structure yields -0.539 dBi (radiation efficiency = -6.764 dB, total efficiency = -7.826 dB). In contrast, the proposed hybrid design attains a realized gain of 8.05 dBi with radiation efficiency of -1.20 dB and total efficiency of -2.20 dB, representing a gain enhancement of approximately 3.9 dB over silicon-only and more than 8.5 dB over gold-only configurations.

These results demonstrate that integrating the gold grating with the Panda-ring resonator strengthens plasmonic coupling and improves the conversion of confined WGM energy into free-space radiation. The proposed structure therefore operates as both an optical resonator and an efficient plasmonic nanoantenna, making it suitable for near-infrared and optical wireless communication applications.

School of Telecommunication Engineering
Academic Year 2025

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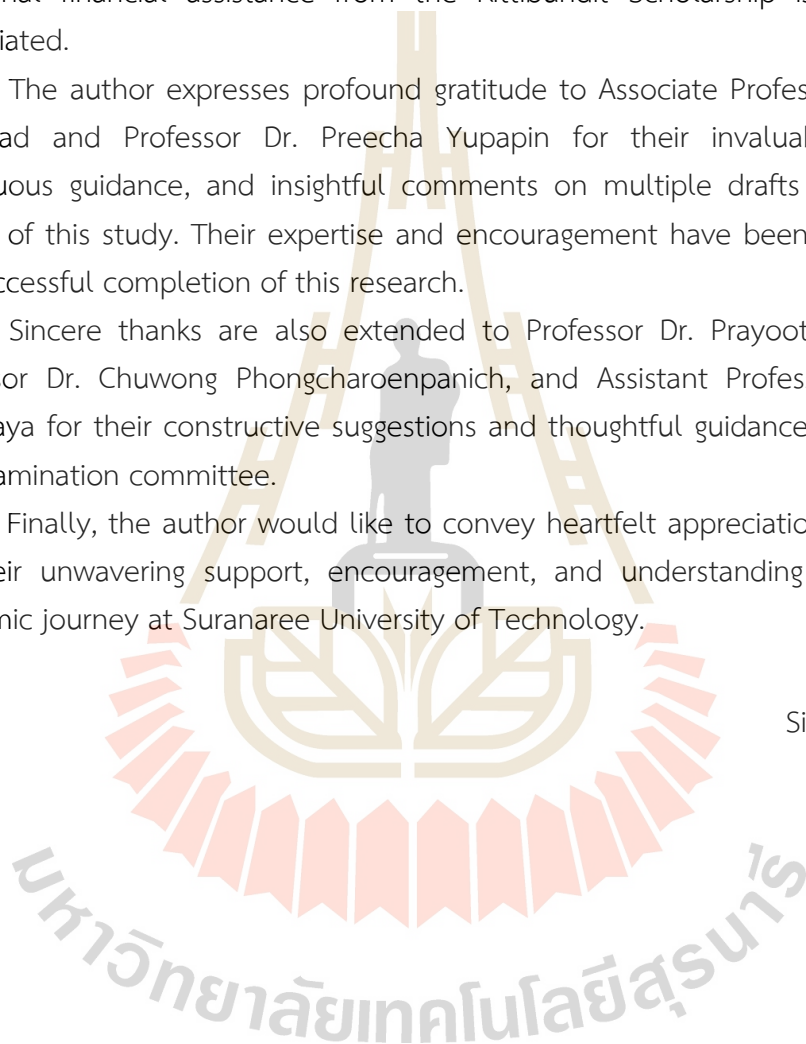


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CHAPTER I

INTRODUCTION

1.1 Background of problems

Electromagnetic waves span a wide range of frequencies, from radio waves to optical and ultraviolet regimes. Among these, optical and sub-terahertz frequency bands have attracted increasing attention in modern telecommunications because they can support ultra-high data transmission rates, reaching tens of gigabits per second and beyond. In contrast, conventional electronic-based transmission media are fundamentally limited by bandwidth constraints, dispersion, and electronic processing speed. Moreover, the generation, amplification, and manipulation of ultrashort optical pulses using purely electronic circuits require complex architectures and high implementation costs.

An alternative and more efficient approach is to perform signal transmission and processing directly in the optical domain, enabling key operations such as amplification, power splitting, wavelength-division multiplexing, and switching without intermediate optical-to-electrical conversion. This paradigm forms the foundation of advanced optical and hybrid wireless-optical communication systems, where optical and near-optical electromagnetic waves play a central role.

From a classical electromagnetic perspective, metals exhibit high reflectivity at visible frequencies, which prevents electromagnetic waves from propagating through bulk metallic materials. Consequently, metals have traditionally been employed as cladding layers in waveguides and resonant structures operating at microwave and far-infrared frequencies. In these low-frequency regimes, metals can be modeled as good conductors because electromagnetic fields penetrate only a shallow region beneath the metal surface. However, as operating frequencies increase toward the near-infrared and visible spectrum, field penetration into metals becomes significant, resulting in increased ohmic losses. This behavior poses a major challenge to straightforward downscaling of conventional photonic devices that operate efficiently at lower frequencies. At even higher frequencies in the ultraviolet regime, metals may exhibit dielectric-like behavior that can allow electromagnetic wave propagation within the material.

While alkali metals may demonstrate ultraviolet transparency due to their nearly free-electron response, noble metals such as gold and silver experience strong absorption arising from interband electronic transitions (Maier, 2007). In this context, plasmonic phenomena provide a compelling framework for overcoming limitations imposed by conventional photonic and electronic technologies. A plasmon is defined as the quantum of collective oscillation of free electrons with respect to the fixed positive ion background in a metal. Analogous to photons in optical waves, plasmons describe charge-density oscillations that can strongly interact with electromagnetic fields. Plasmons are commonly classified into three categories: nanoparticle plasmons, volume plasmons, and surface plasmons. Among these, surface plasmons are of particular interest because they are confined to metal–dielectric interfaces and exhibit strong coupling with incident electromagnetic waves, giving rise to surface plasmon polaritons (SPPs).

Surface plasmon polaritons are hybrid electromagnetic waves formed through coupling between photons and free electrons at a metal surface. They propagate along the metal–dielectric interface while decaying exponentially in the direction normal to the surface. Due to this strong field confinement, SPPs enable electromagnetic energy to be concentrated well below the diffraction limit. Although the theoretical foundations of surface plasmon propagation have been established for decades, plasmonics has experienced rapid growth driven by its potential applications in nanoscale devices, integrated circuits, and high-frequency communication systems (Kik & Brongersma, 2007).

The renewed interest in plasmonics is largely motivated by the unique physical properties of SPPs, which can be rigorously analyzed using Maxwell's equations. SPP fields exhibit maximum intensity at the metal surface and decay rapidly away from the interface, resulting in extreme field localization. Plasmonics therefore serves as a conceptual and practical bridge between electronics and photonics, addressing key limitations in both domains. Electronic systems are constrained by carrier transit times and parasitic effects, while photonic systems are fundamentally limited by diffraction-induced device footprints. As a result, plasmonic nanostructures offer a unique combination of photonic-speed operation and electronic-scale dimensions, making them particularly attractive for next-generation high-frequency communication technologies (Brongersma & Shalaev, 2010). Within this framework, nonlinear optical effects and surface plasmon polaritons form the theoretical foundation of this research. Nanoplasmonics enables the manipulation, guiding, and radiation of electromagnetic waves at dimensions far below the diffraction limit, thereby opening

new opportunities for antenna and transceiver design at optical and sub-terahertz frequencies.

In this thesis, a plasmonic nanoantenna based on a panda-ring resonator circuit integrated with a gold grating on a cylindrical structure is proposed for telecommunications applications. The panda-ring resonator consists of a central ring coupled with two side rings embedded within a double linear waveguide configuration. Such plasmonic nanoantenna structures have gained increasing attention due to their tunable resonant characteristics across a wide frequency spectrum. The OptiFDTD simulation platform is employed to analyze the electromagnetic behavior of the proposed structure, particularly the formation of whispering gallery modes that enable dual-mode operation: (i) a wireless optical link, such as light fidelity (LiFi) communication, and (ii) a guided optical link through fiber-based networks. To further evaluate antenna performance from a telecommunications perspective, key parameters extracted from OptiFDTD simulations are utilized in MATLAB to analyze radiation characteristics, including directivity and gain, thereby assessing the feasibility of the proposed plasmonic nanoantenna as a wireless radiating element for high-frequency communication systems.

1.2 Research objectives

The primary objective of this research is to investigate and develop a plasmonic nanoantenna framework suitable for high-frequency communication systems, with an emphasis on understanding the underlying electromagnetic and plasmonic mechanisms that govern radiation and resonance behavior. The specific objectives of this research are as follows:

1.2.1 To study plasmonic phenomena and surface plasmon polariton (SPP) behavior in order to establish a fundamental understanding of how plasmonic effects can be exploited to enhance the performance of nanoantenna structures in telecommunications applications.

1.2.2 To numerically investigate a plasmonic nanoantenna based on a panda-ring resonator configuration, focusing on its electromagnetic response, resonance characteristics, and radiation behavior through full-wave simulations.

1.2.3 To analyze the radiation performance of the proposed plasmonic nanoantenna, including field confinement, directivity, and gain, in order to evaluate its feasibility as a radiating element for optical and near-optical wireless communication systems.

1.2.4 To assess the potential of the proposed structure for dual-mode operation, supporting both guided-wave (fiber-based) and wireless optical communication scenarios at the standard telecommunication wavelength of 1.55 μm .

1.3 Scope and limitation of the study

1.3.1 The methodical processes of plasmonic nanoantenna in the recent and future communications are presented in this thesis.

1.3.2 The response of proposed plasmonic nanoantenna is simulated by OptiFDTD and CST microwave studio program.

1.3.3 Numerical analysis of the proposed plasmonic nanoantenna is conducted by MATLAB programming.

1.4 Expected benefits

The primary objective of this research is to design and analyze a plasmonic nanoantenna capable of efficiently converting free-space propagating optical electromagnetic waves into localized or guided waves, and vice versa. By employing a panda-ring resonator integrated with a gold grating structure, the proposed nanoantenna is expected to enhance electromagnetic field confinement and radiation efficiency at the nanoscale.

The outcomes of this research are anticipated to contribute to the development of advanced communication components operating at optical and near-optical frequencies. The proposed plasmonic nanoantenna is designed to support a wide range of applications, including optical communication systems (both wired and wireless), laser-based devices, photodetectors, and emerging technologies such as the Internet of Nano Things (IoNT). Operating at the standard telecommunication wavelength of 1.55 μm , the proposed structure aligns with existing optical fiber infrastructure, thereby increasing its relevance and potential impact in future high-speed communication systems.

1.5 Thesis organization

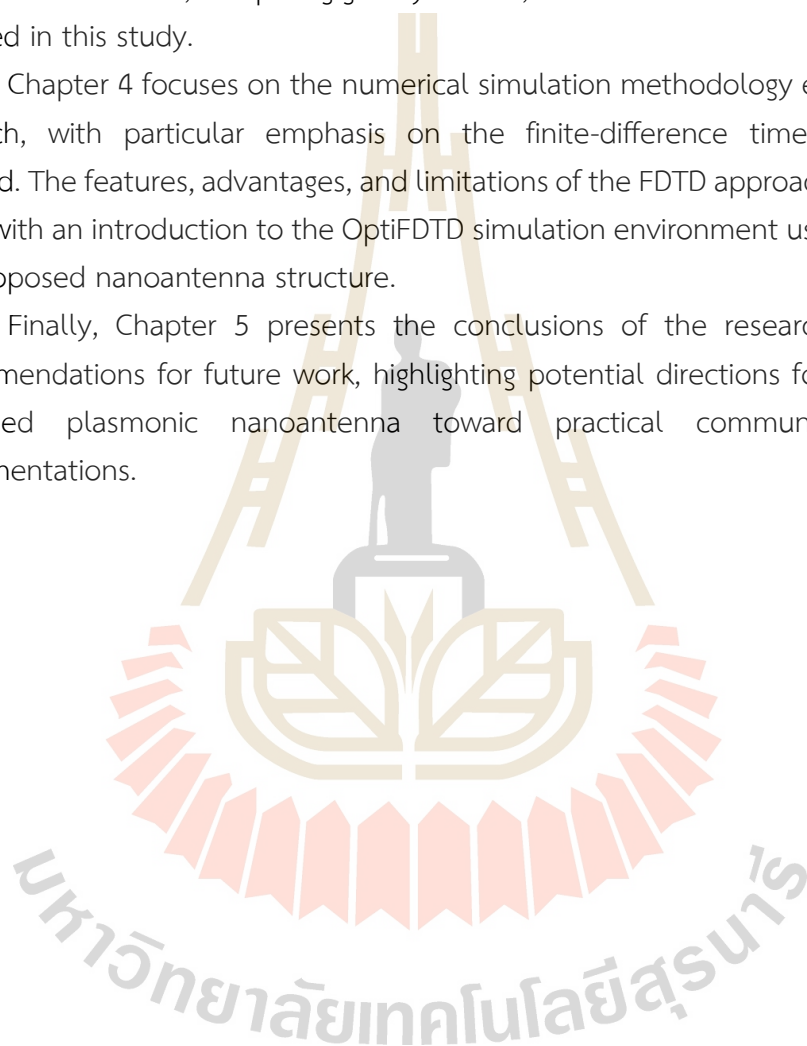
This thesis is organized into five chapters. Chapter 1 introduces the background, motivation, scope, and objectives of the research, establishing the relevance of plasmonic nanoantennas in modern telecommunications engineering. Chapter 2 presents a comprehensive literature review related to plasmonic nanoantenna design, with particular emphasis on panda-ring resonator structures integrated with gold gratings on silicon-based platforms. This chapter also discusses key theoretical

concepts, including comparisons between conventional RF antennas and plasmonic nanoantennas, surface plasmon polaritons (SPPs), and linear and nonlinear plasmonic nanoantenna configurations.

Chapter 3 describes the fundamental theoretical background required for the design of the proposed plasmonic nanoantenna. This chapter covers nonlinear optical properties, the wave equations governing surface plasmon polaritons, the Drude model for metallic materials, whispering gallery modes, and the overall simulation framework adopted in this study.

Chapter 4 focuses on the numerical simulation methodology employed in this research, with particular emphasis on the finite-difference time-domain (FDTD) method. The features, advantages, and limitations of the FDTD approach are discussed, along with an introduction to the OptiFDTD simulation environment used for modeling the proposed nanoantenna structure.

Finally, Chapter 5 presents the conclusions of the research and outlines recommendations for future work, highlighting potential directions for extending the proposed plasmonic nanoantenna toward practical communication system implementations.



CHAPTER II

LITERATURE REVIEW

2.1 Introduction

With the rapid evolution of telecommunications, emerging high-frequency and optical communication paradigms have motivated intensive research into nanoscale radiating and receiving structures. In this context, plasmonic nanoantennas represent optical-frequency counterparts of conventional RF antennas, enabling the coupling between propagating electromagnetic waves and highly localized electromagnetic fields at subwavelength scales. Operating in the micrometer/nanometer wavelength range, plasmonic nanoantennas typically exhibit resonance behavior in the terahertz (THz) regime when expressed in frequency terms. Common platform materials include silicon-based dielectrics and plasmonic metals such as gold and silver, which can support collective electron oscillations and strong field confinement at optical frequencies.

A fundamental distinction between RF/microwave antennas and plasmonic nanoantennas lies in both operating frequency and metal behavior. At RF and microwave frequencies, metals are often modeled as perfect electrical conductors. At optical frequencies, however, electromagnetic fields penetrate metals more significantly, producing higher ohmic losses and altering impedance and radiation behavior. Moreover, metal-dielectric interfaces can sustain surface plasmon polaritons (SPPs)—surface-bound electromagnetic modes generated by the interaction between photons and free electrons in plasmonic metals—leading to near-field enhancement and strong subwavelength confinement (Ozbay, 2006),(Barnes et al., 2003). These characteristics motivate a communication-oriented investigation of plasmonic nanoantenna structures and their integration with resonant photonic circuits. Accordingly, this chapter reviews the literature relevant to the design of plasmonic nanoantennas and highlights the theoretical background required for the proposed approach based on a panda-ring resonator circuit integrated with a gold grating on a silicon cylindrical platform.

2.2 Literature Review

2.2.1 RF and Plasmonic Antennas: Concepts and Key Differences

Antennas are commonly defined as devices that convert electrical power into propagating electromagnetic waves and vice versa (Balanis, 2016). Their importance has led to widespread adoption in RF and microwave systems across numerous applications, including mobile telecommunications, wireless local area networks, Bluetooth, and satellite communications. In parallel, modern wireless devices increasingly demand compact form factors and multi-band operation, driving extensive research into compact and advanced antenna topologies (Patel & Kosta, 2013b),(Patel & Kosta, 2013a).

In optical and nanoscale regimes, the equivalent concept is realized by plasmonic nanoantennas, which are designed to couple far-field optical radiation into strongly confined near-field regions and, conversely, to radiate localized excitations into free space. Compared with RF antennas, plasmonic nanoantennas differ in two critical aspects. First, the perfect-conductor approximation becomes invalid at optical frequencies because fields can penetrate into metals, leading to higher dissipative losses. Second, metal-dielectric interfaces support SPP modes, enabling nanoscale confinement and enhancement effects that do not occur in the same manner in classical RF antenna structures, (Barnes et al., 2003; Ozbay, 2006). As a consequence, plasmonic nanoantennas may exhibit strong field localization in subwavelength gaps, which can serve as effective feed/receive regions for coupling energy into or out of the nanoantenna system (Sundaramurthy et al., 2005).

In addition, optical-frequency light-matter interactions at the nanoscale introduce physical effects that require refined modeling beyond classical RF antenna design assumptions. This has motivated strong research efforts to extend well-established RF antenna concepts to optical nanoantenna counterparts, including impedance interpretation, radiation tuning, and coupling control in plasmonic structures.

2.2.2 Comparison Between RF and Plasmonic Nanoantennas

RF antennas generally have characteristic dimensions on the order of millimeters to centimeters, while optical nanoantennas typically scale to hundreds of nanometers. Despite this size disparity, both aim to control the emission and reception of electromagnetic radiation. A representative example of an RF antenna is the microstrip patch antenna, which is widely used due to its low profile, manufacturability, and low cost (Pozar D.M., 1995). However, conventional microstrip patches may suffer from moderate gain and narrow bandwidth, which can be mitigated through geometry

modifications (e.g., slots, meanders) or the integration of engineered materials such as metamaterials (Pozar D.M., 1995). At visible and near-infrared frequencies, an optical counterpart of the patch concept is the nanopatch antenna, which can be realized by a metallic nanocube separated from a metal film by a thin dielectric spacer. At resonance, a highly localized plasmonic mode can form in the nanogap region, producing strong field enhancement and enabling tunable resonance through geometrical variation (Akselrod et al., 2014). While such optical structures can provide intense near-field localization, their radiation patterns and directionality may differ significantly from RF patch antennas, reflecting differences in material response and wavelength-scale interactions (Lassiter et al., 2013),(Moreau et al., 2012).

In general, RF antennas have dimensions on the order of several centimeters. They are extremely important devices in modern wireless communications. On the other hand, optical nanoantennas, with typical dimensions on the order of a few hundred nanometers, have several important optical applications due to their ability to achieve extremely high field values localized in subwavelength.

An example of an RF microstrip patch antenna and an optical patch nanoantenna are presented in Figure 2.1, the geometry of the microstrip patch antenna is shown in Figure 2.1(a) and its radiation pattern measured at 1.41 GHz. It is composed of a $56.4 \times 56.4 \text{ mm}^2$ square metallic patch placed over a 1.5 mm dielectric substrate. The substrate is terminated by a 1 mm thick ground plane. Microstrip patch antennas have the advantages of small size, ease of fabrication and low cost, which make them ideal candidates to build compact printed antennas at radio frequencies (Pozar D.M., 1995). They also have few disadvantages, such as moderate gain and narrow bandwidth. Their disadvantages can be overcome by incorporating in their geometry metallic meander elements, inductive slots and metamaterials. The bandwidth of microstrip patch antennas can be increased by mounting the metallic patch on a ground plane with a thicker dielectric spacer.

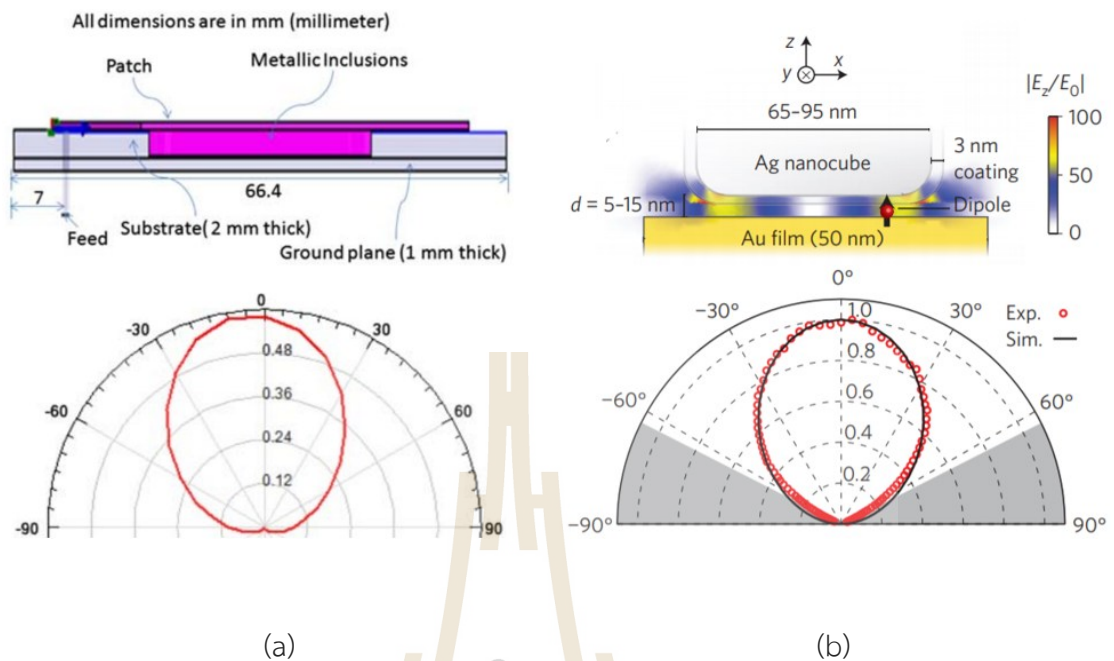


Figure 2.1 The comparison of RF and an optical patch nanoantenna

(a) RF microstrip patch antenna (Patel & Kosta, 2013a)

(b) optical patch nanoantenna (Akselrod et al., 2014)

In visible frequencies, the optical counterpart of the RF patch antenna is the nanopatch antenna, which consists of a silver nanocube placed over a gold film separated by a thin dielectric layer (Akselrod et al., 2014). The geometry of this nanoantenna configuration is presented in Figure 2.1(b) and its directional radiation pattern. The nanocube's side length ranges between 65 and 95 nm and the gap size can range from 5 to 15 nm in this design, as it is presented in Figure 2.1(b). At the resonant frequency, a localized plasmon mode is formed inside the nanogap of this nanoantenna (Akselrod et al., 2014) and the dominant electric field component in this region is oriented towards the normal z direction (Figure 2.1(b)). This particular nanopatch antenna can have field enhancement with maximum values approaching 100 for 5 nm gap and 80 nm nanocube side length. The resonance of this nanoantenna can be easily tuned from 500 nm to 900 nm by varying the nanocube size or the nanogap thickness (Lassiter et al., 2013),(Moreau et al., 2012). Note that the nanopatch antenna is less directional, as it is demonstrated in Figure 2.1(b). And in addition, there are differences in other parameters. Which can be shown as in Table 2.1

Table 2.1 The difference between RF and Plasmonic nanoantennas

List of comparison	RF antenna	Plasmonic nanoantenna
Interested field range	Far-field region	Near- field
Source	Feeding device	Direct light excitation
Cause of waves	Current	Surface plasmon
Supported theories	Maxwell equation	Maxwell equation
Antenna size	mm or cm	μm or nm
Interested Domain	Frequency	Wavelength
Resonant frequency	KHz-GHz	THz
Skin dept	20-30 nm	Skin dept > Diameter of antenna
Electron	Few electrons participate	Complete electrons participate

Table 2.1 shows the difference between RF and Plasmonic nanoantennas. One of interested comparison list is the cause of wave that plasmonic nanoantennas can radiate for functional as will be discussed in the next topic.

2.2.3 Surface plasmon polaritons (SPPs)

The studies on surface plasmons were started in the early nineteenth century. In 1902, Professor Robert W. Wood observed some unexplainable features during the measurement of reflected light from metal grating. Two years later in 1904, Maxwell-Ganett used the newly proposed Drude model for metals and small spherical particle electromagnetics by Lord Rayleigh to explain the reflection of vivid and bright colors from metal doped glasses. In 1908, Gustav Mie computed the scattering of an electromagnetic wave by a homogeneous dielectric sphere which is widely in use today (Maier, 2007).

About sixty years later, in 1956, David Pines investigated collective energy losses in solids in a theoretic manner and attributed these losses to collective electron oscillations in solids. He named these oscillations Plasmon (Pines, 1956). In 1957, Rufus Ritchie published a paper on plasma losses by fast electrons in thin films, he showed in his research that plasmon modes can be formed on metal surface. This was the first time where the surface plasmons were theoretically studied (Ritchie, 1957). One year later, John J. Hopfield introduced and described the term Polariton for coupled oscillations between fast electrons and light in a transparent medium by showing that the ordinary semiclassical theory of the absorption of light by exciton

states is not completely satisfactory (Hopfield, 1958). About seventy years after Wood initial experiments, in 1968, Ritchie et al, described the non-ordinary behavior of Metal Grating by surface plasmon resonance theory. In the same year, considerable progress within surface plasmon studies on metal films achieved by Andreas Otto, Erich Krestschman and Heinz Raether made research in this field simpler than ever.

During the aforementioned period, surface plasmon properties were well studied and exploited. However, the relation between optical properties of metal Nano-particles and this surface plasmons were not yet established. In 1970, more than sixty years after Ganett research on metal doped glasses, Kreibig and Zacharias compared electrical and optical responses of gold and silver Nano-particles in a research. In this research, the theory of surface plasmons was used for the very first time to explain optical properties of metal Nano-particles. The work within the field of surface plasmons and energy exchange between fast electrons and electromagnetic fields were continued until the year 1974 where Cunningham et al used the term surface plasmon polaritons for this phenomenon (Kretschmann & Raether, 1968).

Another breakthrough was achieved in the field of metal-optic in the same year. Fleischmann et al, observed Raman spectra of Pyridine molecules absorbed at a silver (Ag) electrode. The Raman spectra (i.e. energy exchange between photons and molecule oscillations) due to surface Plasmons was significantly intense at silver electrode, however, the importance of this phenomenon was not fully understood at the time. All these findings and experiments has made it possible to step into the world of surface plasmon polaritons (SPPs).

Surface Plasmon, defined by full name Surface Plasmon Polaritons (SPPs), are electromagnetic excitations existing at the interface between a metal and a dielectric material. The nature of these quasi-particles originates from the fact that the electromagnetic wave is captured at the interface of two (metal-dielectric) media. As it is shown in Figure 2.2, oscillations in load density excites the electromagnetic wave that can propagate in relatively long distances (from micrometers to even millimeters, depending on the material and operating frequency). These electromagnetic fields can be analyzed using Maxwell equations. In recent decades, these waves have been nominated of optic dimension reduction in two dimensions so that they are able to overcome diffraction limit.

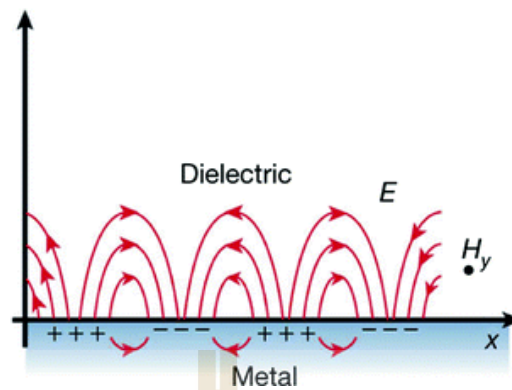


Figure 2.2 Surface Plasmon at the interface of dielectric and metal (Brongersma & Shalaev, 2010).

2.2.4 Plasmonic Nanoantennas: Linear and Nonlinear Configurations

Plasmonic nanoantennas have been widely studied because they enable strong light-matter interaction at subwavelength scales, facilitate coupling between far-field radiation and localized sources, and offer the possibility of realizing wireless links between nanocircuit components (Brongersma & Shalaev, 2010). In general, nanoantenna configurations may be grouped into linear and nonlinear categories.

1) Linear nanoantennas

Usually, RF and optical antennas have linear, reciprocal and passive response. RF dipole antennas are the simplest and most widely used type among the linear antenna configurations. The optical dipole antenna is shown in Figure 2.3 (Al & Engheta, 2008). It is composed of two plasmonic metallic nanorods separated by a nanogap, where inductive or capacitive nanoloads can be placed to achieve tunable performance and impedance matching to the incident radiation. Note that theoretical and experimental studies of different optical nanodipole configurations have been presented by many research groups during the recent years.

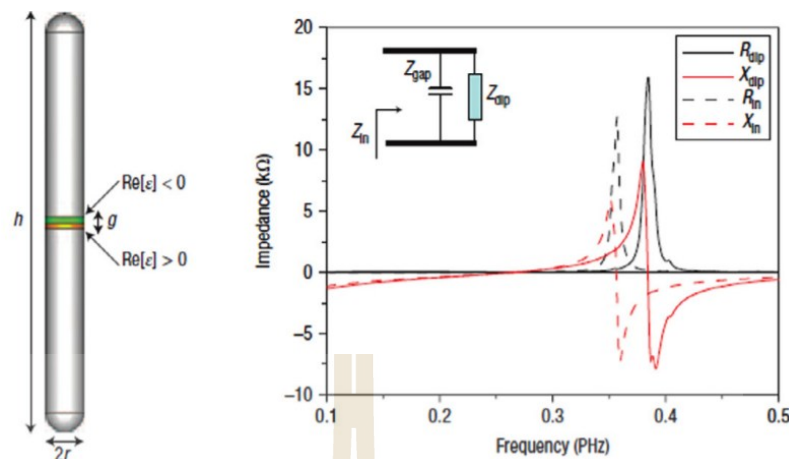


Figure 2.3 Plasmonic nanodipole antenna and its impedance

An alternative exciting application of linear nanoantennas is the potential to create ultrafast and broadband optical wireless communication channels. Nanoscale receiving and transmitting dipole antennas for wireless broadcast applications have been presented in reference (Alù & Engheta, 2010). A nanoscale dipole nanoantenna wireless link shown in Figure 6a can be used instead of purely wired plasmonic waveguide channels. Plasmonic waveguides act as feeds to the transmitting and receiving nanodipole antennas in the configuration shown in Figure 2.3, the magnetic field distribution of the wireless link's transmitter is computed with full-wave electromagnetic simulations for loaded (left) and unloaded (right) nanoantennas.

The unloaded configuration corresponds to the case when the nanogap of the nanoantenna is filled with air. In the loaded configuration, the nanogap is filled with appropriate nanodisk loads in order the nanodipole's impedance to be tuned and matched to the surrounding free space. In the unloaded case, a substantial amount of the input power transmitted to the nanoantenna is reflected back to the feeding plasmonic waveguide.

This is evident by the creation of strong standing waves at the feeding waveguide, as it can be seen in the right side of Figure 2.4, this effect results in poor radiation performance. However, when the nanoantenna is loaded with appropriate nanodisks (loaded case shown in the left side in Figure 2.4), excellent matching is achieved at the resonant frequency and the power transmitted from the plasmonic waveguide to the nanoantenna is efficiently radiated to free space with almost no back reflections.

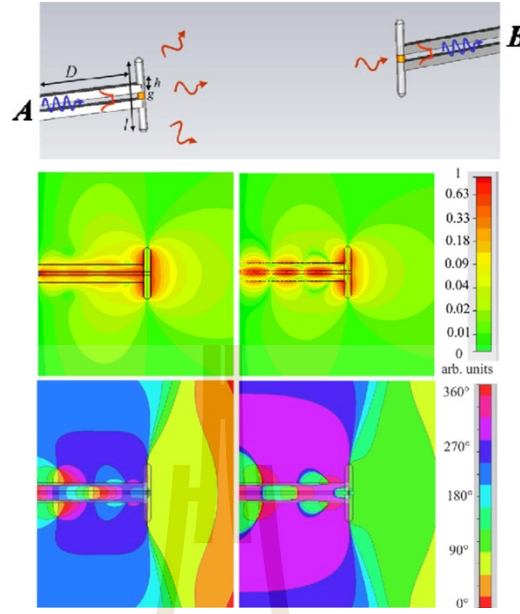


Figure 2.4 Nanodipole antennas as transmitter and receiver.

2) Nonlinear nanoantennas

Until now, we have studied nanoantennas loaded with linear elements, such as nanoinductors and nanocapacitors, and their series and parallel combination. However, nanoantennas can also be loaded with nonlinear optical materials. In this configuration, boosted nonlinear functionalities can be achieved due to the strong confinement and enhancement of the far-field radiation at the nanoantenna's gap, where the nonlinear material will be placed. The design principles of nonlinear optical antennas are based on the same rich physics of the well-established research area of nonlinear optics. The work in this promising research field originated in the pioneering experiment of second harmonic generation observed by illuminating nonlinear crystals (Franken et al., 1961). It exploits the nonlinear relationship between electric field $\mathbf{E}(\mathbf{t})$ and resulting nonlinear polarization $\mathbf{P}(\mathbf{t})$ (Novotny, 2007),(Y. R. Shen, n.d.)

$$\begin{aligned}\mathbf{P}(\mathbf{t}) &= \varepsilon_0 \left[\chi^{(1)} \mathbf{E}(\mathbf{t}) + \chi^{(2)} \mathbf{E}^2(\mathbf{t}) + \chi^{(3)} \mathbf{E}^3(\mathbf{t}) + \dots \right] \\ &\equiv \mathbf{P}^{(1)}(\mathbf{t}) + \mathbf{P}^{(2)}(\mathbf{t}) + \mathbf{P}^{(3)}(\mathbf{t}) + \dots\end{aligned}\quad (2.1)$$

In equation (2.1), ε_0 is the vacuum permittivity and $\chi^{(s)}$ is the sth-order susceptibility of the nonlinear material.

For example, the plasmonic nanopatch antenna can be used to enhance several nonlinear optical processes. It exhibits robust scattering response, which can be controlled by the material placed at the nanogap, combined with strong field enhancement at this nanoregion. The design of a nonlinear plasmonic nanopatch antenna is presented in Figure 2.5 (Argyropoulos et al., 2014).

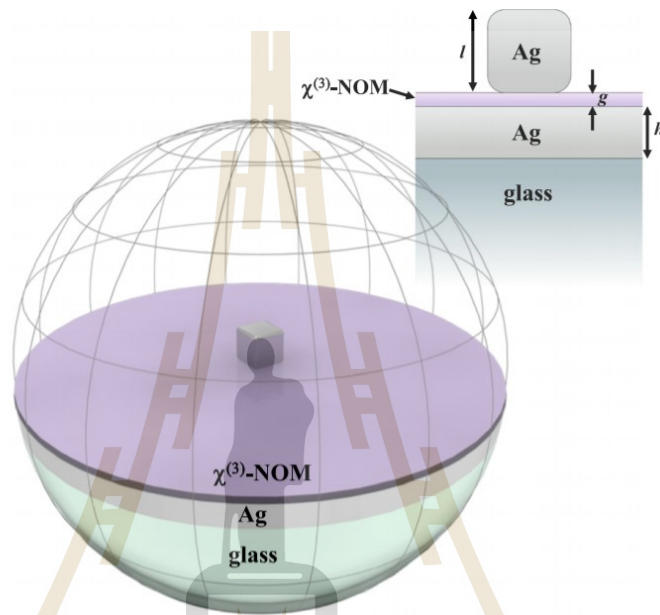


Figure 2.5 Film coupled nonlinear nanopatch antenna (Argyropoulos et al., 2014).

It is built by a silver nanocube. The metallic nanocube is separated with the silver substrate by a thin spacer layer. This spacer layer is made of Kerr nonlinear optical material with relative permittivity. This nonlinear material can be either semiconductor or polymer. The metallic silver is placed above a glass semi-infinite slab with refractive index. In this review paper, the nonlinear analysis of the film coupled nonlinear nanopatch antenna is limited to third order Kerr nonlinear effects in order to demonstrate optical hysteresis and all-optical switching processes. However, this structure can also have other nonlinear applications, such as enhanced second/third harmonic generation and four wave mixing. Note that the metallic parts of the plasmonic nanopatch antenna are simulated using the experimentally measured permittivity of silver (Palik, 1985).

Subsequently, we study the nonlinear Kerr effect of the nanoantenna. The nanoantenna gap and its nonlinear response is triggered when the input intensity of the impinging radiation is increased. To accurately describe the Kerr nonlinearity of

this material is given as a function of intensity (Boyd, 2007): $n = n_0 + n_2 I$, where n_0 is the linear part of the refractive index, n_2 is the nonlinear Kerr coefficient and I is the intensity inside the Kerr material loaded in the nanogap given by $I = 1/2 \epsilon_0 |\mathbf{E}|^2$. The nonlinear optical response resulting from loading the Kerr nonlinear material in the gap of the nanoantenna array is calculated using the analytical method presented in reference (Zhou et al., 2010).

The plasmonic nanoantenna's design is different from that of the RF and microwave antenna since it operates in the high-frequency regime which is the optical frequency. The electromagnetic field penetrates the metal at a depth called skin depth that results in increasing the inertia as shown by the conduction electrons when an illumination occurs, leading to a delay in their response. The electrons are modeled by the light that strikes the metal and couples to the electron plasma, which leads to the formation of rapid oscillation. The effect of the metallic electrons only responds to the effective wavelength, which is a function of the plasma wavelength and incident beam wavelength (Chau et al., 2019; Zhou et al., 2010). Plasmonic nanoantennas are also applied in the field of nanoscale imaging and spectroscopy (Bailo & Deckert, 2008; Cubukcu et al., 2006; Fort & Grésillon, 2008; Hartschuh, 2008; Hartschuh et al., 2004) where the efficiency of light emission and absorption can be increased by plasmonic nanoantennas (Dey et al., 2010; Gao et al., 2010; H. Shen et al., 2013). They are also applied in the field of coherent ultrafast nanophotonics, where the fast emission can be used in femtosecond on-chip electronics (Karnetzky et al., 2018), and so much more.

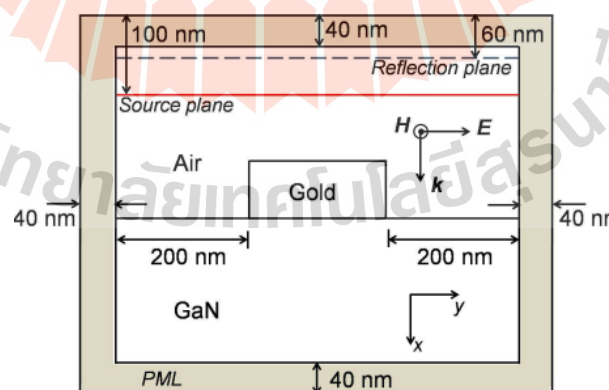


Figure 2.6 A sketch of gold nanorod optical antenna (Dattoma et al., 2011).

Several researchers reported different designs of plasmonic nanoantennas. For example, Dattoma et al. (Dattoma et al., 2011) used a gold nanorod placed on top of gallium nitride substrate as shown Figure 2.6, and studied the dependence of the gold nanorod's resonance wavelength. In this case, the optical nanoantenna is formed in the wavelength from 500 to 1400 nm. Sasmita et al. (Dash et al., 2019) studied the performance of graphene plasmonic nanoantenna, where the graphene is placed on top of SiO_2/Si substrate as shown in Figure 2.7, in which the frequency ranging from 2.56 to 4.98 THz is studied.

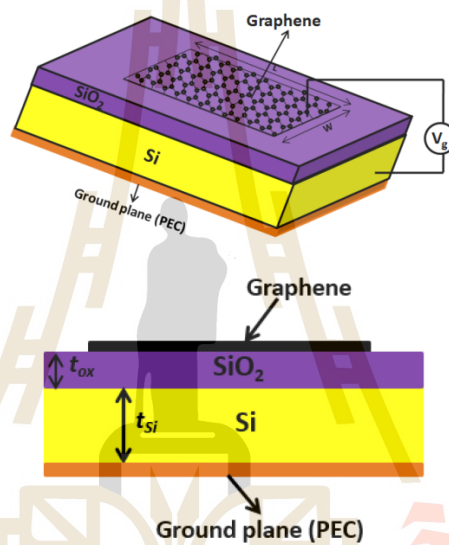


Figure 2.7 A graphene plasmonic nanoantenna (Dash et al., 2019).

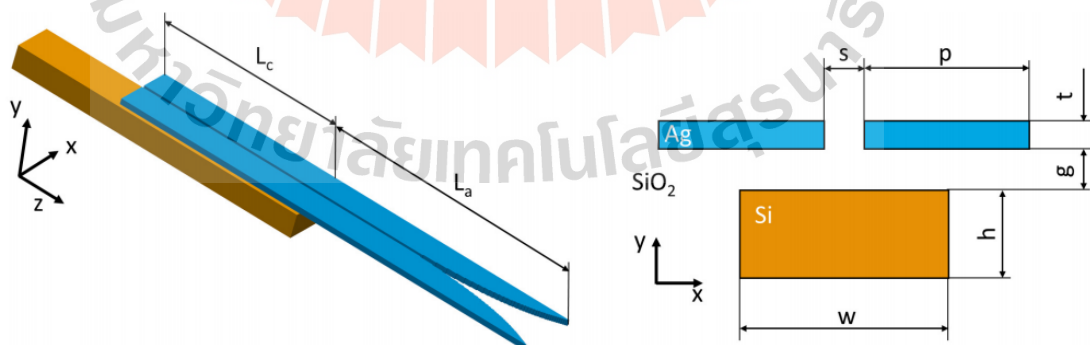


Figure 2.8 Vivaldi plasmonic nanoantenna placed on a silicon substrate (Bellanca et al., 2017).

Bellanca et al. (Bellanca et al., 2017) designed a Vivaldi plasmonic nanoantenna placed on a silicon substrate for wireless optical communication as shown in Figure 2.8, wherein the performance of the plasmonic nanoantenna in the wavelength of 1550 nm is reported. Seyed et al. (Hosseininejad et al., 2018) designed a graphene plasmonic nanoantenna placed on the gallium arsenide substrate as illustrated in Figure 2.9, in which radiation efficiency of this antenna in the frequency of 1–5 THz was studied and obtained.

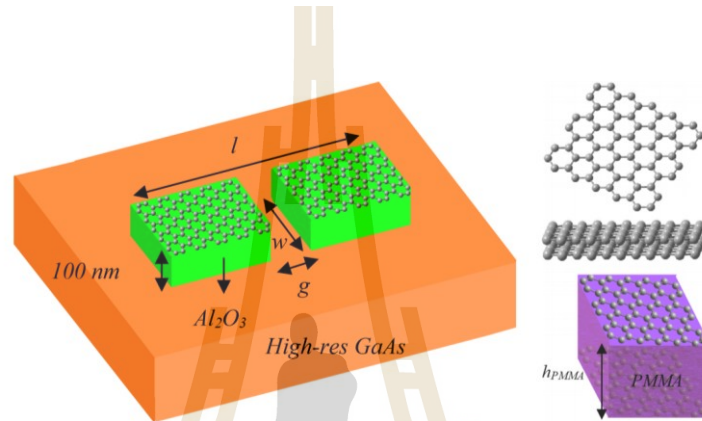


Figure 2.9 A graphene plasmonic nanoantenna placed on the gallium arsenide substrate (Hosseininejad et al., 2018).

Giannini et al. (Giannini et al., 2010) studied the scattering efficiency of the plasmonic nanoantenna made of a semiconductor in the frequency ranging from 1 to 3 THz, in which the near-field enhancement was studied as well. Whispering gallery mode of light is a phenomenon where light waves are trapped inside a ring or microring. The effect of nonlinearity in whispering gallery mode made it have many applications ranging from sensing to optical wireless communication (Braginsky et al., 1989). Yang and Li applied the concept of whispering gallery mode in plasmonic nanocavity that is made of gold nanospheres and quantum dots to study the dependence of light emission on whispering gallery mode (Yang & Li, 2018). Ernst and Albert made use of plasmonic whispering gallery cavities made of gold in studying the surface plasmon resonant modes of the plasmonic whispering gallery cavities which have potential applications in optical nano-antennas (Vesseur & Polman, 2011). Trong and Chang studied the whispering gallery mode resonances in ZnO microspheres embedded with gold nanoparticles and how these WGM resonances can be enhanced (Ngo & Chang, 2017)

2.2.5 Panda-ring resonator circuit

Plasmonic nanoantenna comes in various forms, one of them is a plasmonic circuit consisting of micro/nanoring. This circuit has various advantages because its fabrication is easy and flexible integration, which has been applied by many applications. The microring resonator formed by a Panda-ring circuit has a good advantage, where the Panda-ring structure increases the nonlinear effect. The structure has two small rings alongside the main microring as shown in Figure 2.10. In application, the whispering gallery mode output signals can be applied in either wireless or cable transmissions. When it is a wireless connection, the light fidelity (LiFi) network can be employed using the concept of whispering gallery mode (WGM), the WGM beam as shown in Figure 2.11.

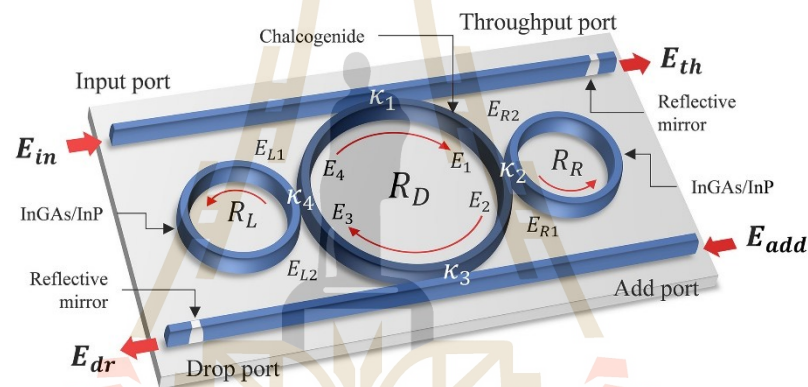


Figure 2.10 Panda-ring resonator circuit (Youplao et al., 2018).

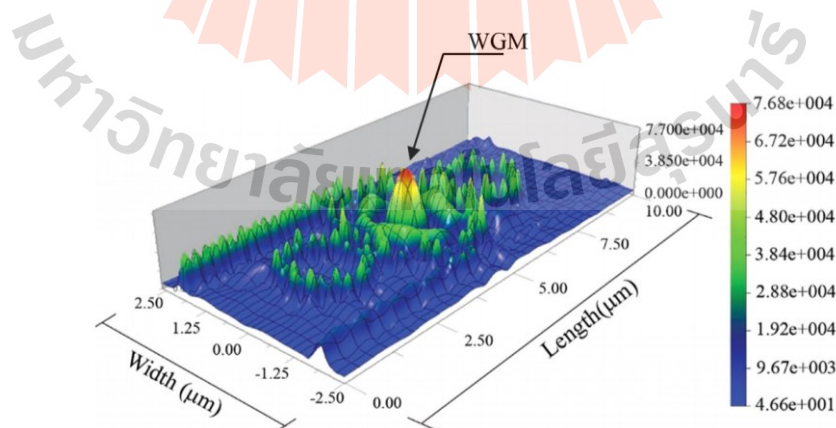


Figure 2.11 The whispering gallery mode (WGM) beam (Chaiwong et al., 2019).

Plasmonic nanoantenna using Panda-ring resonator circuit will be designed for different applications in biomedical, communication (optical, wired, wireless), spectroscopy and imaging, internet of nano things, ultra-high-speed on-chip communication (SOC) and sensors. Plasmonic nanoantenna structures are becoming an area of interest because it supports tuning ability in resonance over the wide frequency spectrum.

Plasmonic nanoantenna can be designed for optical frequency. So, we can design plasmonic nanoantennas for several potential applications like communication (4G, 5G-terabit wireless local/personal area networks), patient's health monitoring (glucose, heart rate, blood sugar, etc.) using wearable sensors and implantable devices. Antenna bandwidth supported at THz frequency is much higher in the range of terabits, wider bandwidth will be achieved. Benefits of the fractal antenna are the reduction in size and multi-band. Initially, the concept will be applied using Panda-ring resonator and the antenna characteristics will be analyzed. Both analytical and simulation models will be presented. The system will be designed using OptiFDTD, MATLAB, and CST microwave studio.

2.3 Chapter summary

This chapter reviewed key literature and theoretical foundations relevant to plasmonic nanoantenna design for high-frequency and optical communication systems. The differences between RF/microwave antennas and plasmonic nanoantennas were highlighted, emphasizing the non-PEC behavior of metals at optical frequencies, increased field penetration and losses, and the role of SPPs in enabling nanoscale confinement. The review also summarized representative linear and nonlinear nanoantenna configurations and discussed how resonant photonic circuits—particularly the panda-ring resonator—can provide tunable and communication-oriented mechanisms for coupling, resonance control, and potential dual-mode operation. The next chapter presents the theoretical framework required to analyze the proposed panda-ring-based plasmonic nanoantenna design.

CHAPTER III

BACKGROUND THEORY

3.1 Introduction

This chapter is devoted to presenting the theoretical background required to support the analysis and discussions developed in the subsequent chapters of this dissertation. The purpose of this chapter is to provide the essential physical and mathematical foundations necessary for understanding the behavior of plasmonic nanoantennas and the underlying analogies employed throughout this research. Key theoretical concepts relevant to surface plasmon polaritons (SPPs) are reviewed, including nonlinear optics and electromagnetic wave equations. The chapter begins with an overview of nonlinear optical theory, which plays a crucial role in describing the interaction between optical fields and nonlinear media. This theoretical framework forms the fundamental basis for analyzing the panda-ring resonator configuration investigated in this thesis. The chapter then proceeds to examine the theoretical properties of surface plasmon polaritons. Starting from the formulation of the governing wave equations, important characteristics of SPPs are discussed, including dispersion relations and spatial field distributions at metal–dielectric interfaces. Particular attention is given to the formation of whispering gallery modes (WGMs) at resonant frequencies, as well as their role in enabling efficient field confinement and their potential applications in optical and wireless communication systems.

3.2 Nonlinear optics

Nonlinear optics (NLO) is a branch of optical science that describes the interaction of light with matter in media whose optical response depends nonlinearly on the strength of the applied electromagnetic field. In a nonlinear medium, the induced polarization density is not directly proportional to the electric field of the incident light, in contrast to linear optical behavior. Such nonlinear responses typically become significant only at high optical intensities, which are commonly achieved using laser sources.

The field of nonlinear optics was formally established following the pioneering experimental work of Franken et al. in 1961, in which second-harmonic generation was first observed. Since then, nonlinear optics has provided a theoretical framework for understanding a wide range of optical phenomena arising from nonlinear light-matter interactions. These interactions can lead to changes in fundamental properties of light, such as frequency, phase, and polarization. One of the most well-known nonlinear optical processes is second-harmonic generation, also referred to as frequency doubling. In this process, incident light at a fundamental frequency generates radiation at twice the original frequency, resulting from the second-order nonlinear polarization induced in the medium. The efficiency of this process is directly related to the square of the applied optical field, highlighting the inherently nonlinear nature of the phenomenon.

In order to describe the optical nonlinearity more clearly, the dependence of the dipole moment per unit volume, or polarization $\mathbf{P}(\mathbf{t})$ of a material system on the applied electric field strength $\mathbf{E}(\mathbf{t})$ is considered. In conventional linear optics the dependence of induced polarization on the electric field strength is linear. This can be defined by the following relationship

$$\mathbf{P}(\mathbf{t}) = \varepsilon_0 \chi^{(1)} \mathbf{E}(\mathbf{t}) \quad (3.1)$$

Where the constant of proportionality $\chi^{(1)}$ is known as the linear susceptibility and ε_0 is the vacuum permittivity. In nonlinear optics, the optical response can be described by generalizing Eq. (3.1) where the polarization $\mathbf{P}(\mathbf{t})$ is expressed as a power series in the field strength $\mathbf{E}(\mathbf{t})$ as

$$\begin{aligned} \mathbf{P}(\mathbf{t}) &= \varepsilon_0 \left[\chi^{(1)} \mathbf{E}(\mathbf{t}) + \chi^{(2)} \mathbf{E}^2(\mathbf{t}) + \chi^{(3)} \mathbf{E}^3(\mathbf{t}) + \dots \right] \\ &\equiv \mathbf{P}^{(1)}(\mathbf{t}) + \mathbf{P}^{(2)}(\mathbf{t}) + \mathbf{P}^{(3)}(\mathbf{t}) + \dots \end{aligned} \quad (3.2)$$

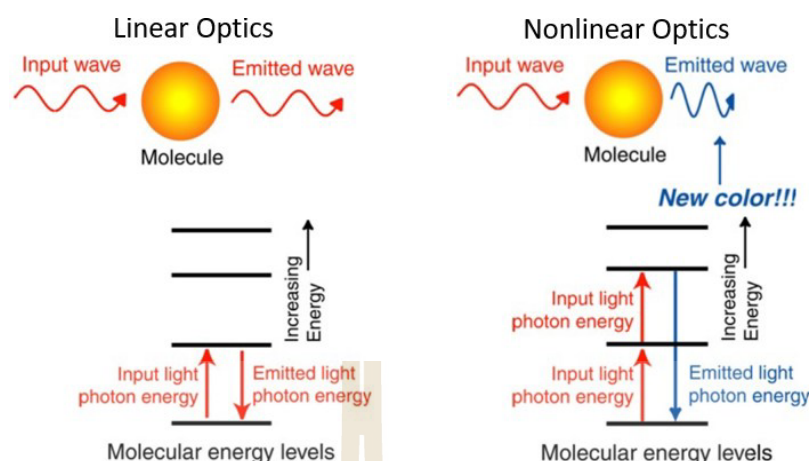


Figure 3.1 The comparison of Linear and Nonlinear optics and their effect (Boyd, 2007).

The quantities $\chi^{(2)}$ and $\chi^{(3)}$ are the second-order and third-order nonlinear optical susceptibilities, respectively. For simplicity, the fields $\mathbf{P}(\mathbf{t})$ and $\mathbf{E}(\mathbf{t})$ in equation (3.2) are assumed as scalar quantities. In writing equations (3.1) and (3.2) in the given forms, it is assumed that the polarization at time (t) depends only on the instantaneous value of the electric field strength. This assumption also implies (according to Kramers-Kronig relations) that the medium is lossless and dispersionless (Boyd, 2007).

The most usual way to explain the nonlinear optic phenomenon is based on the relationship between the polarization $\mathbf{P}(\mathbf{t})$ and the applied electric field strength $\mathbf{E}(\mathbf{t})$ as given in Eq. (3.2). The reason for polarization being important in the description of nonlinear optical phenomenon is that a time-varying polarization can act as a source of new components of the electromagnetic field.

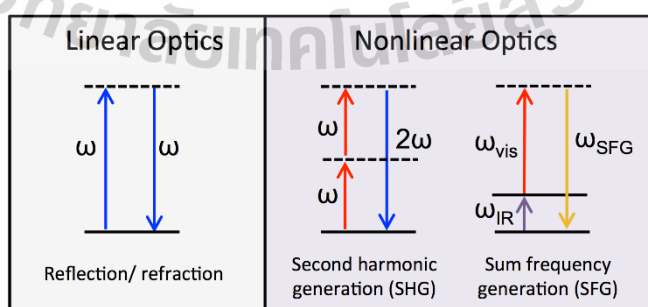


Figure 3.2 The Harmonic comparison of Linear and Nonlinear optics (Boyd, 2007).

The $\mathbf{P}^{(2)}(\mathbf{t})$ in Eq. (3.2) is often expressed as the second order nonlinear polarization and $\mathbf{P}^{(3)}(\mathbf{t})$ is often expressed as the third order nonlinear polarization. The physical process that results in generation of these polarizations are completely different. The generation of second order nonlinear polarization is dependent on the medium symmetry, for example in a symmetrical medium the second order nonlinear factor is zero and therefore no second order nonlinear polarization is generated. $\chi^{(2)}$ This is the case for some liquids, gases, amorphous solids (glass) and many crystals with central symmetry. The third order nonlinear polarization is however generated regardless of the symmetry (Boyd, 2007).

Depending on the susceptibility order (e.g. $\chi^{(2)}, \chi^{(3)}, \dots$) of the nonlinear medium, different optical phenomenon can be generated. Examples are the second harmonic generation, sum frequency generation (SFG), difference frequency generation (DFG), optical rectification (OR) or the generation of third harmonic. The third harmonic generation are further described in this thesis.

3.2.1 Third-order polarization

From Eq. (3.2) we see

$$\mathbf{P}^{(3)}(\mathbf{t}) = \epsilon_0 \chi^{(3)} \mathbf{E}^{(3)}(\mathbf{t}) \quad (3.3)$$

If all frequency components of $\mathbf{E}(\mathbf{t})$ is considered the expression for $\mathbf{P}^{(3)}(\mathbf{t})$ gets very complicated. Therefore, a simple case is considered here where the applied field is monochromatic (i.e. composed of a single frequency), given as

$$\mathbf{E}(t) = \mathbf{E} \cos(\omega t) \quad (3.4)$$

Using the $\cos^3(\omega t)$ expansion, and inserting (3.4) into (3.3) the nonlinear polarization is obtained as follows

$$\mathbf{P}^{(3)}(t) = \frac{1}{4} \epsilon_0 \chi^{(3)} \mathbf{E}^3 \cos(3\omega t) + \frac{3}{4} \epsilon_0 \chi^{(3)} \mathbf{E}^3 \cos(\omega t) \quad (3.5)$$

The first term of Eq. (3.5) shows the generation of third harmonic. The second term describes a nonlinear contribution to the polarization at the frequency of the incident field. Each of these terms are further elaborated.

3.2.2 Third harmonic generation

The first term of equation (3.5) gives a response at frequency 3ω which is created by an applied field at frequency ω . This term leads to the process of third harmonic generation which is illustrated in Figure 3.1. As shown in part (b) of the figure, three photons of frequency ω are destroyed and one photon of frequency 3ω is generated.

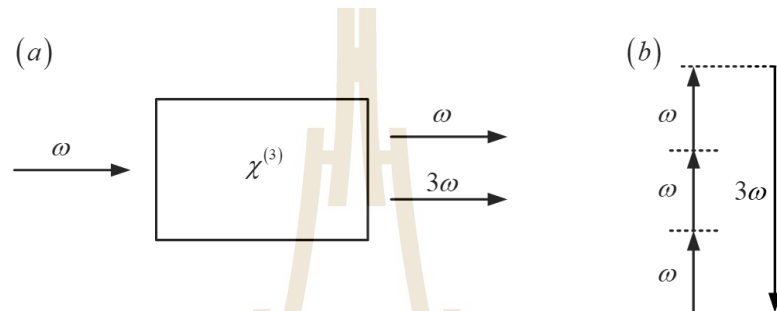


Figure 3.3 Third harmonic generation (Boyd, 2007).

(a) Geometry of the interaction.

(b) Energy-level description.

The phenomenon of travelling whispers with a series of specularly reflected sound rays making up chords of the circular gallery. Clinging to the walls the sound should decay in intensity only as the inverse of the distance rather than the inverse square as in the case of a point source of sound radiating in all directions. This accounts for the whispers being audible all round the gallery.

3.2.3 Dependence of refractive index on light intensity

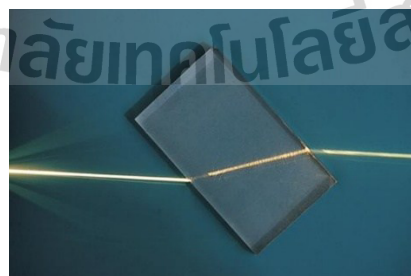


Figure 3.4 A ray of light being refracted in a plastic block (Boyd, 2007).

The second term in Eq. (3.5) describes a nonlinear contribution to the polarization at the frequency of the incident field; this term hence leads to a nonlinear contribution to the refractive index experienced by a wave at frequency ω . The refractive index of many materials is described by the relation

$$n = n_0 + n_2 \langle \mathbf{E}^2 \rangle \quad (3.6)$$

Where n_0 is the linear refractive index, n_2 is an optical constant (sometimes called the second-order index of refraction) that characterizes the rate at which the refractive index increases with increasing optical intensity. The angular brackets around $\mathbf{E}^2$ shows a time average. Therefore, if we assume that the optical field is of the form

$$\mathbf{E}(\mathbf{t}) = \mathbf{E}(\omega) e^{-j\omega t} \quad (3.7)$$

So that

$$\langle \mathbf{E}^2(\mathbf{t}) \rangle = 2\mathbf{E}(\omega)\mathbf{E}^*(\omega) = 2|\mathbf{E}(\omega)|^2 \quad (3.8)$$

We find that

$$n = n_0 + 2n_2 |\mathbf{E}(\omega)|^2 \quad (3.9)$$

The changes occurred in the refractive index through equations (3.6) to (3.9) is called Kerr effect. In Kerr effect, the refractive index of a medium (or its electrical conductivity) changes proportionally to the square of the strength of the applied static electric field (Boyd, 2007).

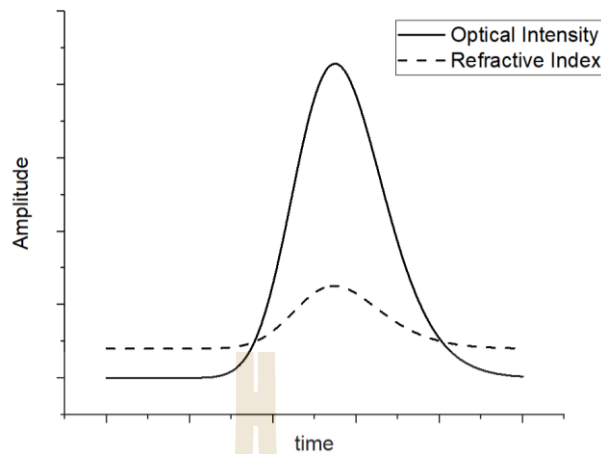


Figure 3.5 Changes of refractive index due to changes of intensity which called Kerr effect.

For Panda-ring resonator structure, Kerr effect which is given by the refractive index equation, and whose relationship is given as $n = n_0 + n_2 I = n_0 + n_2 P / A_{eff}$, where n_0 and n_2 are the linear and nonlinear refractive indices, respectively. Next, I is the optical intensity and P is the optical power, where A_{eff} is the effective mode core area of the device is. For the microring resonator, the effective mode core areas range from 0.1 to 0.50 μm^2 (Arumona et al., 2020).

3.3 Wave equations

As discussed previously, surface plasmon polaritons (SPPs) are strongly confined to the vicinity of a metal–dielectric interface and exhibit pronounced sensitivity to the physical and electromagnetic conditions of the surface. This high surface sensitivity constitutes a fundamental characteristic of SPPs and underpins their efficient excitation and interaction with external perturbations at the interface. As a result, SPP-based phenomena have been widely exploited in various applications, including the investigation of surface absorption properties, characterization of surface roughness, and the development of highly sensitive chemical and biological sensing platforms.

To establish a rigorous understanding of the fundamental behavior of SPPs at a single flat interface, as well as in metal–dielectric multilayer structures, it is necessary to describe the underlying electromagnetic field relationships governing their propagation. This analysis is most appropriately conducted by starting from the electromagnetic wave equation derived from Maxwell's equations.

Accordingly, the physical properties of surface plasmon polaritons are investigated by applying Maxwell's equations to a planar interface between a conductive medium and a dielectric material. In this thesis, Maxwell's equations are formulated using the International System of Units (SI), and their application provides the theoretical foundation for analyzing SPP dispersion characteristics, field confinement, and surface-bound propagation modes.

$$\nabla \cdot \mathbf{D} = \rho_{ext} \quad (3.10)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (3.11)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (3.12)$$

$$\nabla \times \mathbf{H} = \mathbf{J}_{ext} + \frac{\partial \mathbf{D}}{\partial t} \quad (3.13)$$

These equations link to the four macroscopic fields $\mathbf{D}$ (the dielectric displacement), $\mathbf{E}$ (the electric field), $\mathbf{H}$ (the magnetic field), and $\mathbf{B}$ (the magnetic flux density). ρ_{ext} is the external charge density and $\mathbf{J}_{ext}$ is the external current density.

Here we assume that the external charge and current densities are absent. In this case, after combining equations (3.12) and (3.13) we have the central equation of electromagnetic wave theory

$$\nabla^2 \mathbf{E} - \frac{\epsilon}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0 \quad (3.14)$$

The symbol ∇^2 is the Laplacian, ϵ is the dielectric constant and c is the speed of light in vacuum. This equation for practical applications shall be solved separately in regions of constant ϵ , and the obtained solutions shall be matched using appropriate boundary conditions. To map Eq. (3.14) in a form that is proper for description of confined propagating waves, two steps are usually considered. First, a general timeharmonic dependence of the electric field for example, $\mathbf{E}(r, t) = \mathbf{E}(r)e^{-j\omega t}$ is assumed. With this assumption Eq. (3.14) will be of the form

$$\nabla^2 \mathbf{E} - k_0^2 \epsilon \mathbf{E} = 0 \quad (3.15)$$

Where k_0 is the vacuum wave number, Eq. (3.15) is known as the *Helmholtz equation* (Maier, 2007). Next, a geometry is defined for the propagation. For example, a simple one-dimensional case is considered i.e. ε depends only on one spatial coordinate. In this example the waves propagate along the x-direction and show no spatial variation in the perpendicular, in-plane y-direction as given in Figure 3.2, therefore $\varepsilon = \varepsilon(z)$. In the context of electromagnetic surface area, the plane $z = 0$ coincides with the interface containing the propagating waves, which can now be defined as

$$\mathbf{E}(x, y, z) = \mathbf{E}(z) e^{-j\beta x} \quad (3.16)$$

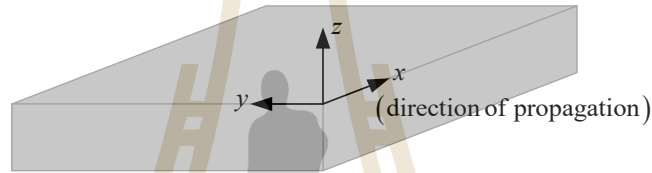


Figure 3.6 Definition of a planar waveguide geometry. The waves propagate along the x-direction in a cartesian coordinate system (Maier, 2007).

The complex parameters $\beta = k_x$ is called the propagation constant of the traveling waves and corresponds to the component of wave vector in the direction of propagation. Inserting Eq. (3.16) into Eq. (3.15) result in the desired form of the wave equation

$$\frac{\partial^2 \mathbf{E}(z)}{\partial z^2} - (k_0^2 \varepsilon - \beta^2) \mathbf{E} = 0 \quad (3.17)$$

A similar equation can be written for the magnetic field $\mathbf{H}$ (Maier, 2007). For the wave equation to be usable in determining the spatial field profile and dispersion of propagating waves, explicit expressions for the different field components of $\mathbf{E}$ and $\mathbf{H}$ are needed. By use of curl equations (3.12) and (3.13) and the time-harmonic dependence $\left(\frac{\partial}{\partial t} = -j\omega\right)$, the following set of coupled equations are achieved

$$\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = j\omega\mu H_x \quad (3.18a)$$

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = j\omega\mu H_y \quad (3.18b)$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = j\omega\mu H_z \quad (3.18c)$$

$$\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} = -j\omega\epsilon E_x \quad (3.18d)$$

$$\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} = -j\omega\epsilon E_y \quad (3.18e)$$

$$\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} = -j\omega\epsilon E_z \quad (3.18f)$$

The set of equation can be written in a more simplified form by considering the propagation along the x-direction (i.e. $\frac{\partial}{\partial x} = j\beta$) and homogeneity in the y-direction (i.e. $\frac{\partial}{\partial y} = 0$) as follows

$$\frac{\partial E_y}{\partial z} = -j\omega\mu H_x \quad (3.19a)$$

$$\frac{\partial E_x}{\partial z} - j\beta E_z = j\omega\mu H_y \quad (3.19b)$$

$$j\beta E_y = j\omega\mu H_z \quad (3.19c)$$

$$\frac{\partial H_y}{\partial z} = j\omega\epsilon E_x \quad (3.19d)$$

$$\frac{\partial H_x}{\partial z} - j\beta H_z = -j\omega\epsilon E_y \quad (3.19e)$$

$$j\beta H_y = -j\omega\epsilon E_z \quad (3.19f)$$

This system allows two sets of solutions with different polarization properties of the propagating waves. The first set are the transverse magnetic (TM) modes, in which only the field components E_x , E_z and H_y are nonzero, and the second set the

transverse electric (TE) modes, where only H_x , H_z and E_y are nonzero. For TM modes, the system of governing equations (3.19) is written as

$$E_x = -j \frac{1}{\omega \epsilon} \frac{\partial H_y}{\partial z} \quad (3.20a)$$

$$E_z = -\frac{\beta}{\omega \epsilon} H_y \quad (3.20b)$$

and the wave equation for TM modes is written as

$$H_x = j \frac{1}{\omega \mu} \frac{\partial E_y}{\partial z} \quad (3.21a)$$

$$H_z = \frac{\beta}{\omega \mu} E_y \quad (3.21b)$$

and the wave equation for TE mode is written as

$$\frac{\partial^2 E_y}{\partial z^2} + (k_0^2 \epsilon - \beta^2) E_y = 0 \quad (3.21b)$$

With these equations available, the description of surface plasmon polaritons can be started.

3.4 SPPs at a single interface

The simplest geometry containing SPPs is that of a single, flat interface as shown in chapter 2. This is between a dielectric, non-absorbing half space ($z > 0$) in which the real dielectric constant is given here as ϵ_2 and an adjacent conducting half space ($z < 0$) characterized by a dielectric function $\epsilon_1(\omega)$, the metallic character implies that $\text{Re}[\epsilon_1(z)] < 0$. For metals this condition is fulfilled at frequencies below the bulk plasmon frequency ω_p , the propagating wave solutions confined to the interface with decay in the perpendicular z -direction are of interest. Looking at TM solutions, using the equation set (3.20) in both half spaces yields

$$H_y(z) = A_2 e^{-j\beta x} e^{-k_2 z} \quad (3.22a)$$

$$E_x(z) = iA_2 \frac{1}{\omega \varepsilon_0 \varepsilon_2} k_2 e^{-j\beta x} e^{-k_2 z} \quad (3.22b)$$

$$E_z(z) = -A_1 \frac{\beta}{\omega \varepsilon_0 \varepsilon_2} e^{-j\beta x} e^{-k_2 z} \quad (3.22c)$$

for $z > 0$ and

$$H_y(z) = A_1 e^{-j\beta x} e^{k_1 z} \quad (3.23a)$$

$$E_x(z) = -iA_1 \frac{1}{\omega \varepsilon_0 \varepsilon_1} k_1 e^{-j\beta x} e^{k_1 z} \quad (3.23b)$$

$$E_z(z) = -A_1 \frac{\beta}{\omega \varepsilon_0 \varepsilon_1} e^{j\beta x} e^{k_1 z} \quad (3.23c)$$

for $z < 0$. $k_i \equiv k_{zi}$ ($i=1,2$) is the component of the wave vector perpendicular to the interface in the two media. Its multiplicative inverse value, $\hat{z} = 1/|k_z|$, defines the evanescent decay length of the fields perpendicular to the interface, which quantifies the confinement of the wave. The H_y and $\varepsilon_i E_z$ are continuous at the interface which implies that $A_1 = A_2$ and

$$\frac{k_2}{k_1} = -\frac{\varepsilon_2}{\varepsilon_1} \quad (3.24)$$

Note that with the convention of the signs in the exponents in equation sets (3.22) and (3.23), confinement to the interface demands $\text{Re}[\varepsilon_i] < 0$ if $\varepsilon_2 < 0$ i.e. the surface waves exist only at interfaces between materials with opposite signs of the real part of their dielectric permittivities or in other words between a conductor and an insulator. The expression for H_y further must fulfill the wave equation (3.20c), resulting

$$k_1^2 = \beta^2 - k_0^2 \varepsilon_1 \quad (3.25a)$$

$$k_2^2 = \beta^2 - k_0^2 \varepsilon_2 \quad (3.25b)$$

Then the dispersion relation is achieved by combining Eq. (3.24) and (3.25) for SPPs propagating at the interface between the two half spaces

$$\beta = k_0 \sqrt{\frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2}} \quad (3.26)$$

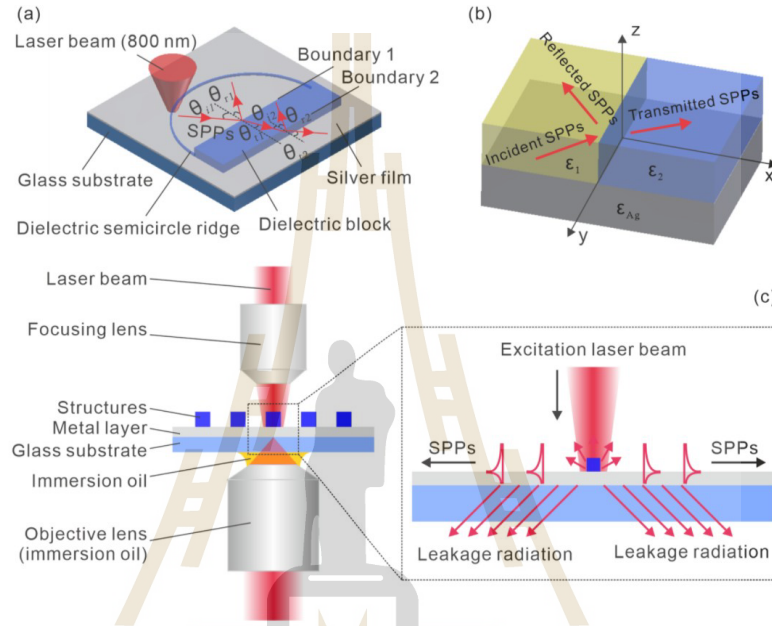


Figure 3.7 Surface plasmon polaritons (SPPs) at the interface (Zheng et al., 2019)

- (a) Geometrical structure.
- (b) Schematic illustration of reflection and transmission.
- (c) Schematic illustration of generating SPPs.

In metals, conduction electrons respond fast when they are illuminated by light or excited by electromagnetic radiation which can cause the electrons to move quasi-freely in metals. The response in metals such as gold is described by the dielectric function that is frequency dependent by using the Drude model which present in the next title.

3.5 Drude model: Drude-Sommerfeld model of the dielectric function

The Drude model of electrical conduction was proposed in 1900 by Paul Drude to explain the transport properties of electrons in materials (especially metals). The model, which is an application of kinetic theory, assumes that the microscopic

behaviour of electrons in a solid may be treated classically and looks much like a pinball machine, with a sea of constantly jittering electrons bouncing and re-bouncing off heavier, relatively immobile positive ions.

The model was extended in 1905 by Hendrik Antoon Lorentz (and hence is also known as the Drude–Lorentz model) to give the relation between the thermal conductivity and the electric conductivity of metals (see Lorenz number), and is a classical model. Later it was supplemented with the results of quantum theory in 1933 by Arnold Sommerfeld and Hans Bethe, leading to the Drude–Sommerfeld model (Derkachova & Kolwas, 2008).

Some of the metal properties, including the optical properties, can be described within the simple free-electron gas Drude-Sommerfeld model of the dielectric function. In the framework of this model, with an external field applied, the conduction electrons move freely between independent collisions occurring at the average rate of γ , the frequency dependent dielectric function $\varepsilon(\omega)$ predicted by Drude-Sommerfeld model:

$$\varepsilon(\omega) = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + j\gamma\omega} = 1 - \frac{ne^2}{\varepsilon_0 m \omega^2} \quad (3.27)$$

Where ε_0 is the relative permittivity of free space. The other n, e and m are the electron density, charge, and mass, respectively. The symbol ω is the angular frequency. Includes the contribution of the bound electrons to the polarizability by introducing phenomenological parameter ε_{∞} . This parameter equals 1 only if the conduction band electrons contribute to the dielectric properties. The dielectric function changes its sign from negative to a positive and real part of the dielectric function to 0. The plasma frequency ω_p is given by:

$$\omega_p = \sqrt{\frac{ne^2}{\varepsilon_0 m}} \quad (3.28)$$

These oscillations are detected through the enhanced absorption at these frequencies of EM radiation passing through thin metal particles. There are also surface plasmons. The plasma frequency depends critically on the shape and size of the particles (not captured by this simple theory) – Au nanoparticles display different colours depending on their size. The surface plasmon (SP) wave is a wave that travels in the direction of the metal–dielectric interface and in the orthogonal direction to it

while decaying evanescently (Gupta, 2018), where the Drude model accounts for free electron conduction of the bound electrons in the metal. The SP wave oscillation is obtained by using an electric field that is the longitudinal oscillation. By using the Maxwell equations, the TM polarization and exponential decay of the electric field are obtained. In this work, the resonant plasma frequency is obtained from the graphical result, where the WGM output at the resonant frequency is obtained.

3.6 Whispering gallery mode (WGM)

The whispering gallery mode (WGM) of wave or energy has been an interesting phenomenon for years (Gupta, 2018), where principally the WGMs can be generated by various forms of waves such as sound waves, electromagnetic waves, heat waves, particle waves, water waves, and gravitational waves. The key behavior of WGM generation is that tunneling effects of the circular-like path motion of a particle wave can introduce the tunneling and collection of energy at a certain position within the system (Adamian et al., 1998; Marinica et al., 2012). One of the most important issues is when the photon travels within the circular-like path device, from which the WGM can be generated by the specific controlled conditions (Madsen & Lenz, 1998; Mason, 1956). In this work, such a device is the nonlinear micro-ring resonator, made by a semiconductor material, from which the WGM can be generated and controlled with the device. To date, many works have been investigated for various applications (Lee et al., 2008; Madsen & Zhao, 1996; Sappajak & Yupapin, 2016; Schulte et al., 2015; Tomofuji et al., 2009; Vahala, 2003).

Principally, the WGMs can be formed by various output signal shapes and structures such as conic beams (Nawrocka et al., 2006), light probes (Gorney et al., 1981), light or particle sources (Mustafa & Russo, 1989), conjugate mirrors (Balle & Flygare, 1981), and artificial eyes (Weiss et al., 1987), all of which are useful for various works. The micro-ring device is known as a Panda ring resonator as shown in Figure 3.8, consisting of a linear or nonlinear center ring with a radius of 1–10 μm and two nonlinear side rings with ring radii of 0.5–2 μm . However, in general the device can be a metallic ring or semiconductor ring, in which the WGM can be formed in the forms of photon, spin, or particle wave by the introduced nonlinear coupling effects from the nonlinear two side rings. By controlling the ring parameters and input source power, the WGMs can be obtained. WGM probes generated by a micro-scale device have been useful for many applications, one very interesting one being a communication device application where the biggest advantage. The whispering gallery mode output signals can be applied in either wireless or cable transmissions. When it is a wireless connection, the light fidelity (LiFi) network can be employed using the concept of

whispering gallery mode (WGM) (Chaiwong et al., 2019; Punthawanunt et al., 2018; Youplao et al., 2018),

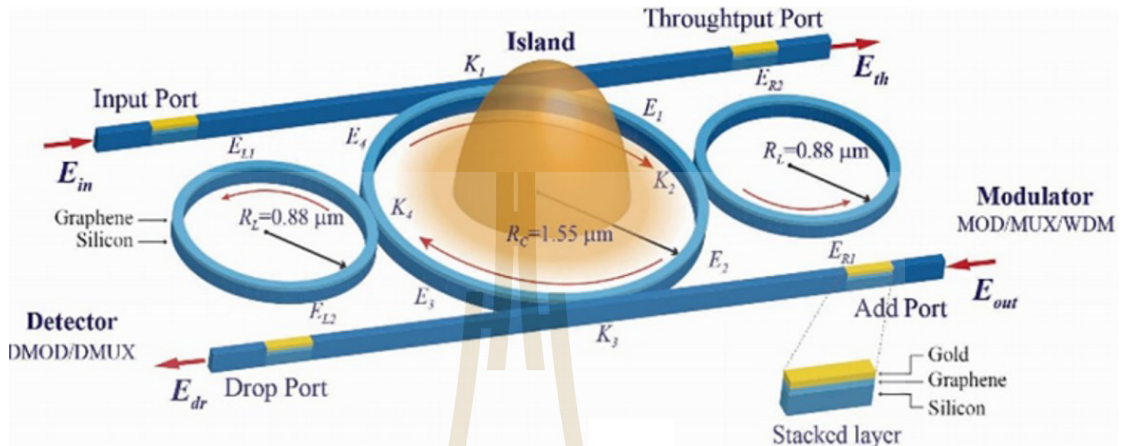


Figure 3.8 Panda ring resonator with WGM island (Chaiwong et al., 2019).

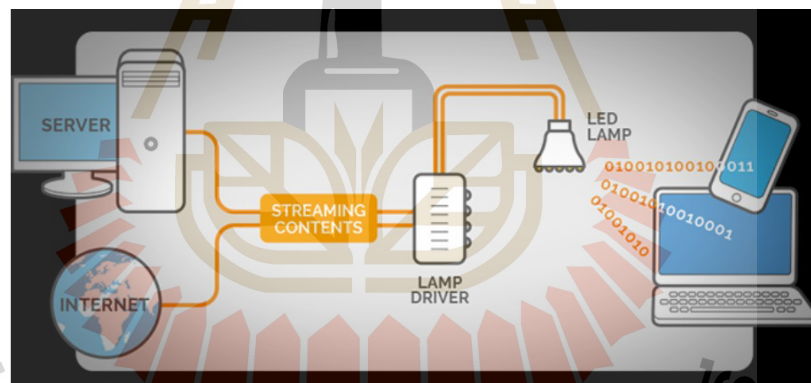


Figure 3.9 The light fidelity (Li-Fi) network (*Light Fidelity (Li-Fi)/Visible Light Communication Market 2022*, n.d.).

Light Fidelity: LiFi (*Light Fidelity (Li-Fi)/Visible Light Communication Market 2022*, n.d.) is a very high speed, two-way wireless communication method which uses visible light from LEDs as the medium for transmitting the data by turning them on and off at very high frequency which human eyes cannot sense. This technology is an apt replacement for currently prevailing WiFi technology as LiFi is considerably faster, has almost 10,000 times broader bandwidth because it uses visible light, and it is safe to operate in electromagnetic sensitive areas. Researchers have reached data rates of

over 224 Gbit/s, which was much faster than typical fast broadband in 2013. LiFi is expected to be ten times cheaper than WiFi. Short range, low reliability and high installation costs are the potential downsides.

Table 3.1 The comparison between WiFi and LiFi.

Properties	WiFi	LiFi
Spectrum used	RF	Visual light
Range	Less than 200 meters	Depends on intensity of light
Cost	High	Low
Security	Less secure than LiFi	More secure
Data transfer speed	108 Mbps (with double channel)	100 times faster than WiFi
Standard	802.11	IEEE 802.15

3.7 Simulation methodology

3.7.1 Features of FDTD method

FDTD is a simple and illustrative method to solve partial differential equations. It uses central difference approximations to discretize the time dependent Maxwell's equations to the space and time partial derivatives. Then by numerical calculation of the extracted equations, it solves the electric field vector components in a special volume at a given instant of time. It then solves the magnetic field vector components in the same volume of space at the next instant of time. To fully establish the desired transient or steady-state field behavior, this process is repeated over and over. It is possible to use the FDTD method for any desired coordination system e.g. Cartesian or cylindrical system. Since the Cartesian coordinate system is more suitable to express crystal photonic structures, the focus of this thesis work is on the FDTD method in Cartesian coordinate system. It is also worth noting that the first version of the OptiFDTD software (the simulation software used in this thesis work is 2-dimensional (2D), where the photonic device is laid out in the XZ plane. The propagation is along z. The y-direction is assumed to be infinite. This assumption removes all the $\partial/\partial y$ derivatives from Maxwell's equations and splits them into two (TM and TE) independent sets of equations.

The 2D computational domain is shown in Figure 3.10. The space steps in the x and z directions are Δx and Δz respectively. Each mesh point is associated

with a specific type of material and contains information about its properties such as refractive index and dispersion parameters (*FDTD Tutorials*, n.d.).

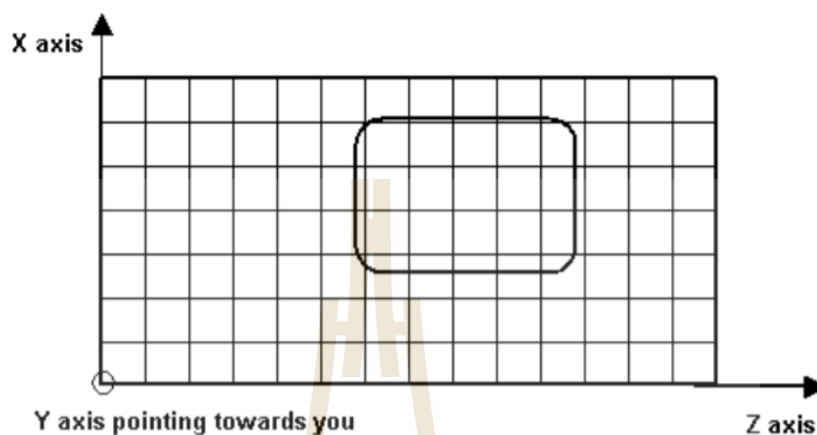


Figure 3.10 Numerical representation of the 2D computational domain (*FDTD Tutorials*, n.d.).

3.7.2 Grid dimensions

The major rule to identify the dimensions of the computational grid domain is that it must be adequately smaller than the wavelength for which the high precision is desired. Prior to understanding the size of the desired computational grid, it is important to decide what accuracy is required. Having ten cells for the highest required frequency wavelength is common. We however know that the wavelength varies depending on the medium, thus to determine the grid dimensions, one has to consider the wavelength against the increase in permittivity coefficient. For example, a medium with high permittivity using evenly distributed mesh points will result in an oversized grid. To overcome this, it's recommended that the grid is realized by use of variable dimensions.

For a better understanding of the requirement of grid dimensions being small than the wavelength, the Nyquist law shall be referred to. According to this law, at least two samples within each wavelength are needed to be able to reconstruct the waveform, and since we are using linear approximation, more cells are needed to boost accuracy. Another reason to consider small grid dimensions is the diffraction error imposed by the FDTD method. This error occurs due to the approximation within the FDTD method which makes electromagnetic waves move with variant frequencies and velocity. The magnitude of these movements (diffraction) depends on the grid

dimension and the direction of propagation as a function of the grid structure. One other important factor in determining the grid dimension is to ensure that the desired geometry is accurately modelled. Often this is automatically achieved due to application of this condition: grid dimension less than $\lambda/10$, except if geometric segments smaller than this are going to be considered in the final design. For example, steps in the model introduce high degree of error when analyzing diffraction from flat interfaces.

3.7.3 Determination of time step to stabilize FDTD algorithm

The most important requirement for each numerical method is its numerical stability and its conditions. Any numerical method such as FDTD is conditionally stable. The stability of FDTD is studied at (Umran S. Inan, 2011) and is fulfilled with the following condition.

$$0 \leq \Delta t \leq \frac{1}{c} \frac{1}{\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}} \quad (3.29)$$

When c is the speed of light in vacuum. In fact, this condition expresses that the speed of numerical phase shall not exceed the speed of light. This is measured by a stability factor (also known as Courant number; S) which is defined as

$$S = c \frac{\Delta t}{\Delta x} \quad (3.30)$$

Thus, if $\Delta x = \Delta y = \Delta z$, then the stability condition will be $S \leq 1/\sqrt{3}$. This can be generalized to n-dimensional FDTD where the stability condition will be $S \leq 1/\sqrt{n}$.

3.7.4 FDTD algorithm

The FDTD method which is also referred to as Yee's algorithm is a numerical analysis technique used for modelling computational electrodynamics. Dr. Yee in 1966 (Yee, 1966) introduced an algorithm for spatial networking of differential and integral Maxwell's equations in time domain. Although many other algorithms were introduced after him, his method is still considered to be the main one. The advantage of Yee's algorithm is in selecting proper differential modes and placing electric and magnetic field components in relation to time and space.

Some of the main features of the Yee's algorithm used in this thesis are, instead of solving the wave equation for either electric or magnetic field modes in time domain, both are solved simultaneously over time. With this approach, the boundary conditions of electric and magnetic field modes are fulfilled simultaneously and explicitly. This is especially important when there is a singular point in a field component. Thus, by calculating both electric and magnetic field modes, multiple problems can be solved without losing accuracy.

Each component of the electric field mode is surrounded by four magnetic field components as shown in Figure 3.10 for TE mode case. Here each field is represented by a 2D array, $E_y(i,k)$, $H_x(i,k)$ and $H_z(i,k)$. The indices i and k account for the number of space steps in the x and z direction, respectively. In fact each electric component is encapsulated by a current (Faraday) loop. Thus, by calculating electromagnetic field components by FDTD algorithm that is originated from Maxwell's differential equations, their integral mode is also achieved. The integral modes are used in determination of boundary conditions and singularities.

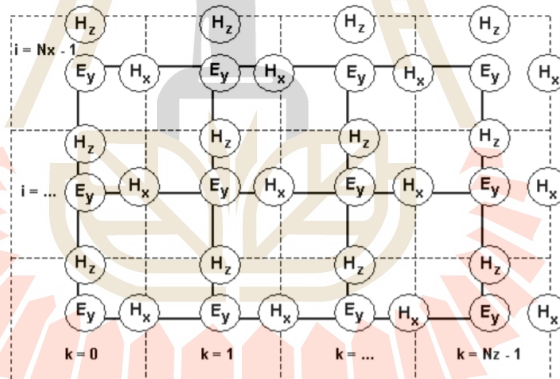


Figure 3.11 Location of the TE fields in the computational domain
(FDTD Tutorials, n.d.).

Any numerical method must fulfill all four Maxwell's equations. In the case of FDTD method, it only deals with the curl of Maxwell's equations. And also due to positioning of the field components, Maxwell's divergence equations are fulfilled at the same time.

Continuity of electric and magnetic field components perpendicular to the interface of two media can be achieved with no need for extra computation as long as the interface is positioned on the computation grid.

Positioned on the computation grid. The version used in this thesis has second order precision.

Electric and magnetic field components are implemented in Leap Frog manner meaning that at any instant of time, only one of the field components are calculated. The usage is explicit and removes the need for matrix inversion.

3.7.5 Numerical decay properties of FDTD

By numerical decay we mean that the propagation of a plain wave within a numerical grid is not dependent on the actual decay relation in the medium under study, but it rather is dependent on the discrete parameters such as $\Delta x, \Delta y, \Delta z$ and Δt . For instance, in vacuum the propagation of plain wave follows the decay relation

$$\frac{\omega^2}{c^2} = (k_x^2 + k_y^2 + k_z^2) \quad (3.31)$$

However, the decay relation of the same wave within FDTD grid is

$$\left[\frac{1}{c\Delta t} \sin\left(\frac{\omega\Delta t}{2}\right) \right]^2 = \left[\frac{1}{\Delta x} \sin\left(\frac{k_x\Delta x}{2}\right) \right]^2 + \left[\frac{1}{\Delta y} \sin\left(\frac{k_y\Delta y}{2}\right) \right]^2 + \left[\frac{1}{\Delta z} \sin\left(\frac{k_z\Delta z}{2}\right) \right]^2 \quad (3.32)$$

From equation 3.32 it is understood that the numerical decay can be reduced to a desired level by reducing $\Delta x, \Delta y, \Delta z$ and Δt . The numerical decay results in slower wave phasor velocity in the FDTD grid than its actual level. Furthermore, within the FDTD grid the wave phasor velocity has anisotropy characteristic, meaning that the phasor velocity of waves with identical frequencies are different in different directions.

3.7.6 PML boundary conditions

One of the principal challenges associated with the finite-difference time-domain (FDTD) method lies in the appropriate truncation of the computational domain. Since numerical electromagnetic simulations are inherently performed within a finite spatial region, it is necessary to restrict the computational grid to the vicinity of the structure of interest in order to achieve computational efficiency. At the same time, it is essential that incident and scattered electromagnetic waves are allowed to exit the computational domain without generating artificial reflections at the boundaries, which would otherwise contaminate the simulation results.

To address this issue, suitable absorbing boundary conditions (ABCs) must be applied at the outer boundaries of the computational grid. In 1994, Béranger

introduced an effective absorption technique in which an artificial absorbing region is placed outside the main computational domain. This region is designed to absorb outgoing electromagnetic waves independently of their frequency and angle of incidence, thereby minimizing reflections at the boundary. Bérenger implemented this approach by numerically solving Maxwell's equations within the absorbing region using a field-splitting formulation, and termed this method the Perfectly Matched Layer (PML). Subsequently, in 1996, Gedney proposed an improved formulation known as the anisotropic perfectly matched layer (APML), which offers several advantages over the original PML scheme, including enhanced numerical stability and improved absorption performance for evanescent and obliquely incident waves [88]. As a result of these advantages, PML-based techniques have become the standard approach for truncating computational domains in modern FDTD simulations.

In this thesis, the anisotropic PML formulation proposed by Gedney is adopted as the absorbing boundary condition for all numerical simulations. This choice ensures accurate modeling of open-boundary electromagnetic problems and reliable evaluation of the radiation and scattering characteristics of the proposed plasmonic nanoantenna structures.

3.8 Chapter summary

This chapter has presented the theoretical foundations required to support the design, simulation, and analysis of the proposed plasmonic nanoantenna. The theories and concepts discussed in this chapter provide the necessary physical and mathematical background for understanding the mechanisms and analogies employed throughout this research. Based on the literature review, the panda-ring resonator has been identified as an effective structure for generating whispering gallery mode (WGM) outputs, which play a significant role in communication-related applications. Accordingly, the fundamental theories of linear optics, surface plasmon polariton (SPP) generation, whispering gallery mode formation, panda-ring resonator circuits, and numerical simulation methodologies have been systematically reviewed and discussed in this chapter. These theoretical considerations establish a solid framework for the numerical implementation and performance evaluation of the proposed plasmonic nanoantenna. In the subsequent chapter, the simulation procedures and detailed analysis of the plasmonic nanoantenna based on the panda-ring resonator circuit are presented and discussed.

CHAPTER IV

DESIGN AND ANALYSIS

4.1 Introduction

This chapter presents the numerical investigation and simulation results of the proposed Panda-ring resonator and plasmonic nanoantenna structures. The analysis is carried out using the Finite-Difference Time-Domain (FDTD) method to study electromagnetic wave propagation, resonant behavior, and field distribution in integrated optical devices. The study begins with the analysis of a silicon linear waveguide as a baseline structure, followed by the investigation of single-ring and double-bus ring resonators to understand coupling mechanisms and resonance characteristics. Subsequently, the Panda-ring resonator is introduced to generate and control whispering-gallery modes (WGMs) for enhanced energy confinement. Finally, the generated WGM is utilized as an excitation source for the proposed plasmonic nanoantenna by integrating a gold grating structure. The far-field radiation characteristics, including gain and radiation efficiency, are analyzed and compared under identical excitation conditions. This systematic approach provides a clear understanding of the transition from photonic resonance to hybrid plasmonic-photonic radiation mechanisms.

4.2 Structural Evolution of Ring Resonator Configurations

The progressive development of the photonic resonator structures investigated in this work is illustrated in Figure 4.1. As shown in the figure, the design evolution begins with a simple silicon linear waveguide and gradually advances toward a more complex Panda-ring resonator configuration. This structured approach allows systematic analysis of electromagnetic wave propagation, resonance formation, coupling behavior, and energy localization at each stage of structural complexity. As depicted in Figure 4.1 (Step 1), the silicon linear waveguide serves as the baseline structure for evaluating reference transmission and guided power propagation. In Step 2, a single-ring resonator is introduced to demonstrate the formation of whispering-gallery-mode (WGM) confinement through evanescent coupling between the bus waveguide and the ring. Step 3 extends the configuration to an add-drop ring resonator, enabling controlled spectral selectivity and wavelength-dependent power routing via dual-waveguide coupling.

Finally, in Step 4, two auxiliary side rings are integrated with the central ring to form the Panda-ring resonator, which enhances WGM localization and enables multi-resonant coupling control. This evolutionary framework, summarized in Figure 4.1, provides clear physical insight into how structural modifications influence resonance characteristics and field distribution. The optimized Panda-ring configuration obtained from this process serves as the fundamental WGM excitation platform for the plasmonic nanoantenna design discussed in the subsequent section.

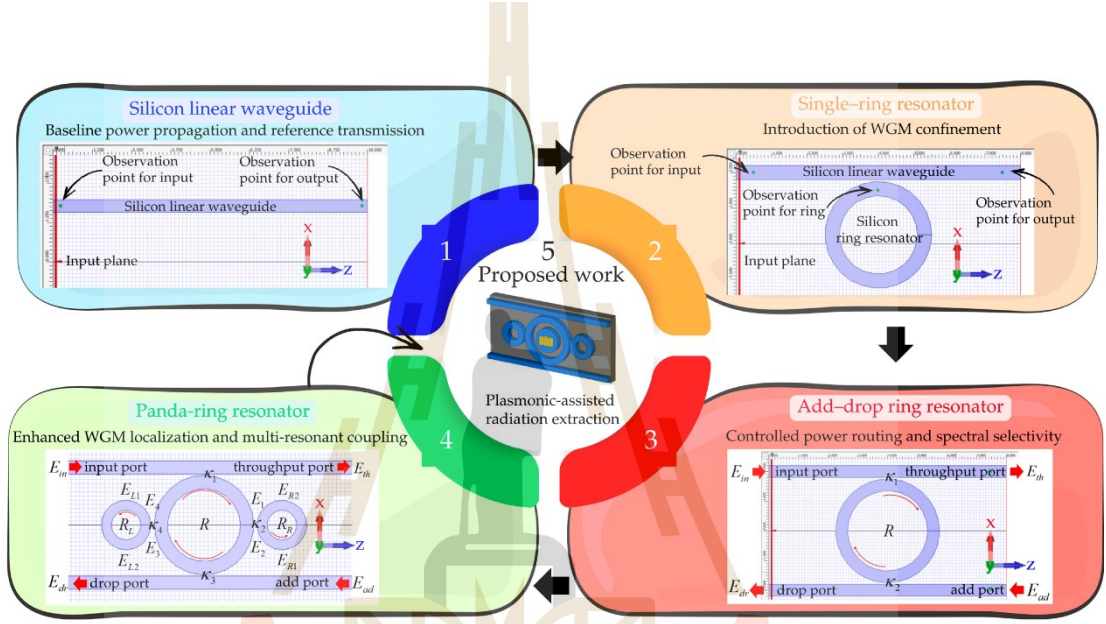


Figure 4.1 Evolution of Ring Resonator Configurations.

4.2.1 Silicon linear waveguide

The silicon linear waveguide is first investigated as the baseline structure for analyzing guided-wave propagation and reference transmission characteristics. As illustrated in Figure 4.2, the waveguide consists of a silicon core embedded in a lower-refractive-index surrounding medium, enabling optical confinement through total internal reflection. The refractive index of silicon at the operating wavelength of $1.55 \mu\text{m}$ is taken as 3.42, while the nonlinear refractive index is $1.3 \times 10^{-13} \text{ m}^2/\text{W}$.

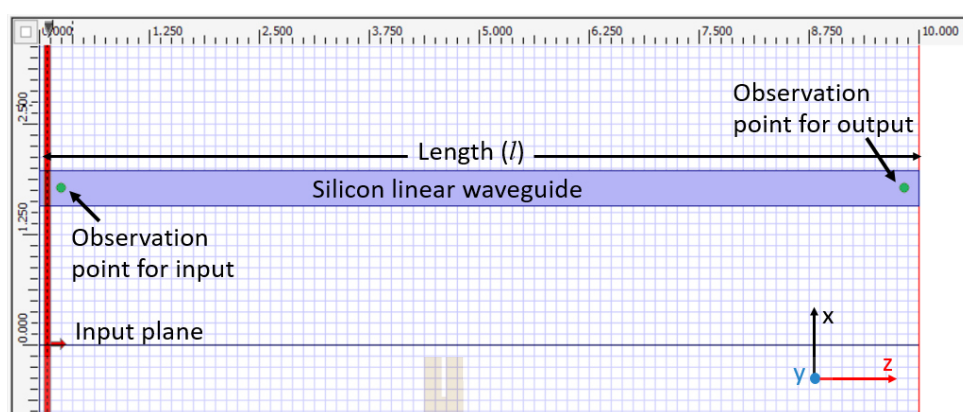


Figure 4.2 The 2D structure of silicon linear waveguide on OptiFDTD program.

The waveguide dimensions are selected to ensure single-mode or quasi-single-mode propagation in the near-infrared region. In this study, the waveguide width and thickness are fixed at $0.5\ \mu\text{m}$, while the propagation length is varied ($10, 20, 50$, and $100\ \mu\text{m}$) to examine attenuation and transmission stability along different distances. A Gaussian-modulated continuous-wave source centered at $1.55\ \mu\text{m}$ is launched at the input plane, and the transmitted optical power is monitored at both input and output observation points.

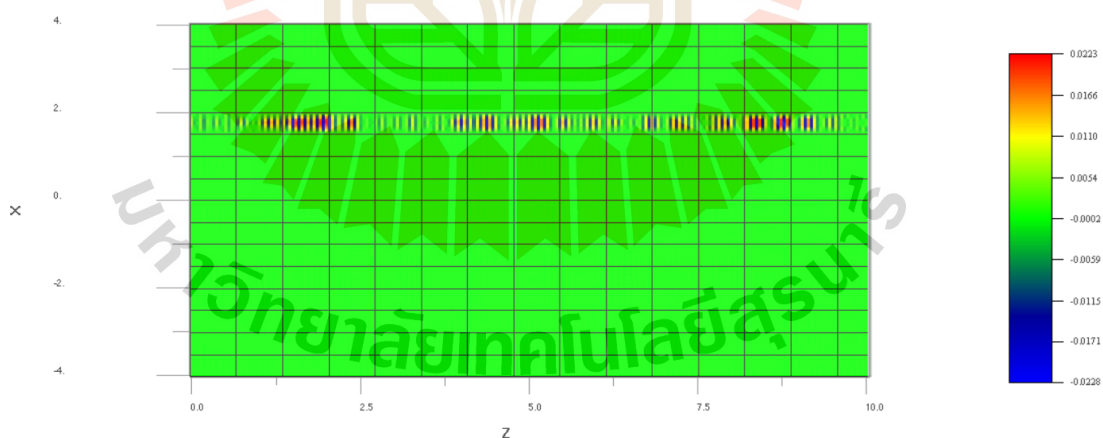


Figure 4.3 The power run along the silicon linear waveguide on OptiFDTD program.

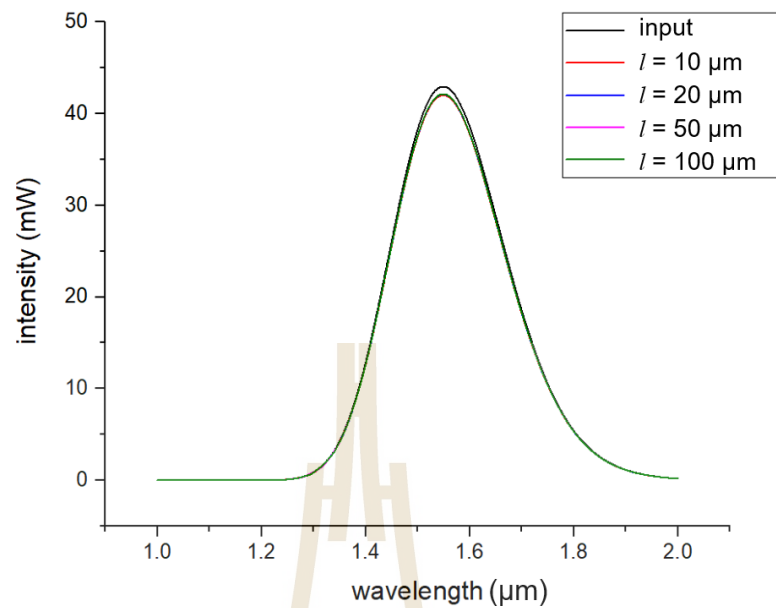


Figure 4.4 The simulated result of silicon linear waveguide with different lengths.

The simulation results, shown in Figures 4.3 and 4.4, demonstrate that optical power propagates along the waveguide with minimal distortion. A slight reduction in output intensity is observed due to propagation loss and intrinsic material attenuation; however, the overall transmission remains stable across different lengths. The similarity in output intensity for various waveguide lengths confirms that the silicon linear waveguide provides consistent and reliable guided-wave behavior within the investigated range.

This baseline analysis establishes a reference transmission level for subsequent resonator configurations. By understanding pure guided propagation without resonant coupling, the influence of ring-induced whispering-gallery modes and coupling effects in later sections can be clearly distinguished and quantitatively evaluated.

4.2.2 Single-Ring Resonator

Following the baseline investigation of the silicon linear waveguide, a single-ring resonator coupled to a bus waveguide is introduced to demonstrate the formation of whispering-gallery-mode (WGM) confinement. As illustrated in Figure 4.5, the structure consists of a straight silicon waveguide positioned in close proximity to a circular ring waveguide. Optical coupling between the bus waveguide and the ring occurs through the evanescent field when the gap separation is sufficiently small. When light propagates along the linear waveguide, a portion of the optical field

penetrates into the surrounding region in the form of an exponentially decaying evanescent wave. If the ring waveguide is placed within this evanescent field region, optical energy can be coupled into the ring. Resonance occurs when the optical phase accumulated over one roundtrip inside the ring satisfies the constructive interference condition.

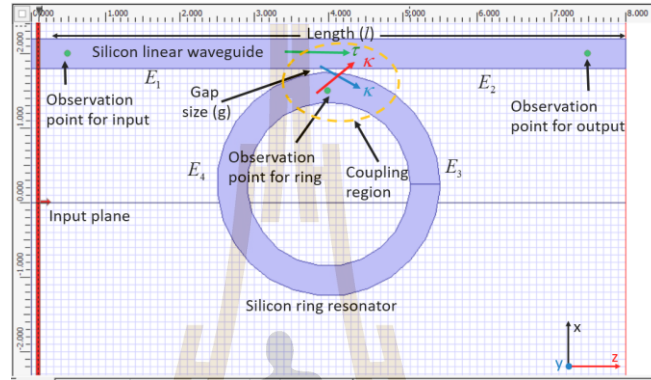


Figure 4.5 The 2D structure of Single-Ring Resonator.

We describe the coupling of light into and out of the resonator in terms of generalized beam splitter relations of the form work (Bogaerts et al., 2012) as shown these equations.

$$E_2 = \kappa E_1 + i\tau E_3 \quad (4.1)$$

$$E_4 = \kappa E_3 + i\tau E_1 \quad (4.2)$$

Where κ and τ are coupling and transmitting coefficient respectively. Both of these coefficient taken to be real quantities that satisfy the relation $\kappa^2 + \tau^2 = 1$ and the electric fields (E_n) are defined with respect to the reference points indicated in Fig. 4.5 Moreover, the transmission or coupling power also depends on coupling length, $L_c = \pi/2k$. In critical coupling $\tau = \alpha$ the transmitted power equals the loss in the ring (Heebner et al., 2004). We find the ring to be on resonance when the phase ϕ is a multiple of 2π , or when the wavelength of the light fits a whole number of times inside the optical length of the ring.

$$\lambda_{res} = \frac{n_{eff}L}{m} \quad ; m = 1, 2, 3, \dots \quad (4.3)$$

Where λ_{res} is the resonance wavelength
 n_{eff} is the effective refractive index
 L is the circumference of the ring waveguide $L = 2\pi r$
 m is the resonance mode

In this study, the resonance wavelength is selected at 1.55 μm . The ring radius is calculated accordingly to satisfy the resonance condition, and the mode number corresponding to stable confinement is determined through simulation. The electric-field distribution shown in Figure 4.6 confirms the formation of multiple resonance modes along the ring boundary, indicating successful WGM confinement.

From Equation 4.3 we get,

$$r = m\lambda_{res} / 2\pi n_{eff}$$

$$r = \frac{m(1.55 \times 10^{-6})}{2\pi(3.42)} \approx (7.213 \times 10^{-8})m ; m = 1, 2, 3, \dots$$

Table 4.1 Radius of ring resonators computation

Mode number (m)	Radius of ring (μm)	Mode number (m)	Radius of ring (μm)
1	0.07	11	0.79
2	0.14	12	0.87
3	0.22	13	0.94
4	0.29	14	1.01
5	0.36	15	1.08
6	0.43	16	1.15
7	0.50	17	1.23
8	0.58	18	1.30
9	0.65	19	1.37
10	0.72	20	1.44

From Table 4.1, the corresponding ring radii for different resonance mode numbers are calculated based on the selected operating wavelength of 1.55 μm . Among these values, the resonance mode number $m = 18$, which corresponds to a ring radius of approximately 1.3 μm , provides a suitable dimension for stable whispering-gallery-mode (WGM) confinement. Therefore, this radius is selected for the design of the single-ring resonator structure shown in Figure 4.5 and is used in the subsequent simulations.

When the silicon ring resonator coupled to a single linear waveguide is simulated using the OptiFDTD program, a portion of the optical field propagating along the bus waveguide is coupled into the ring through the evanescent field interaction. The light propagation behavior is illustrated in Figure 4.6(a), while the formation of the 18th resonance mode along the ring boundary is shown in Figure 4.6(b). The corresponding discrete Fourier transform (DFT) analysis of the electric field along the Y-axis is presented in Figure 4.6(c), confirming the resonant behavior at the selected wavelength.

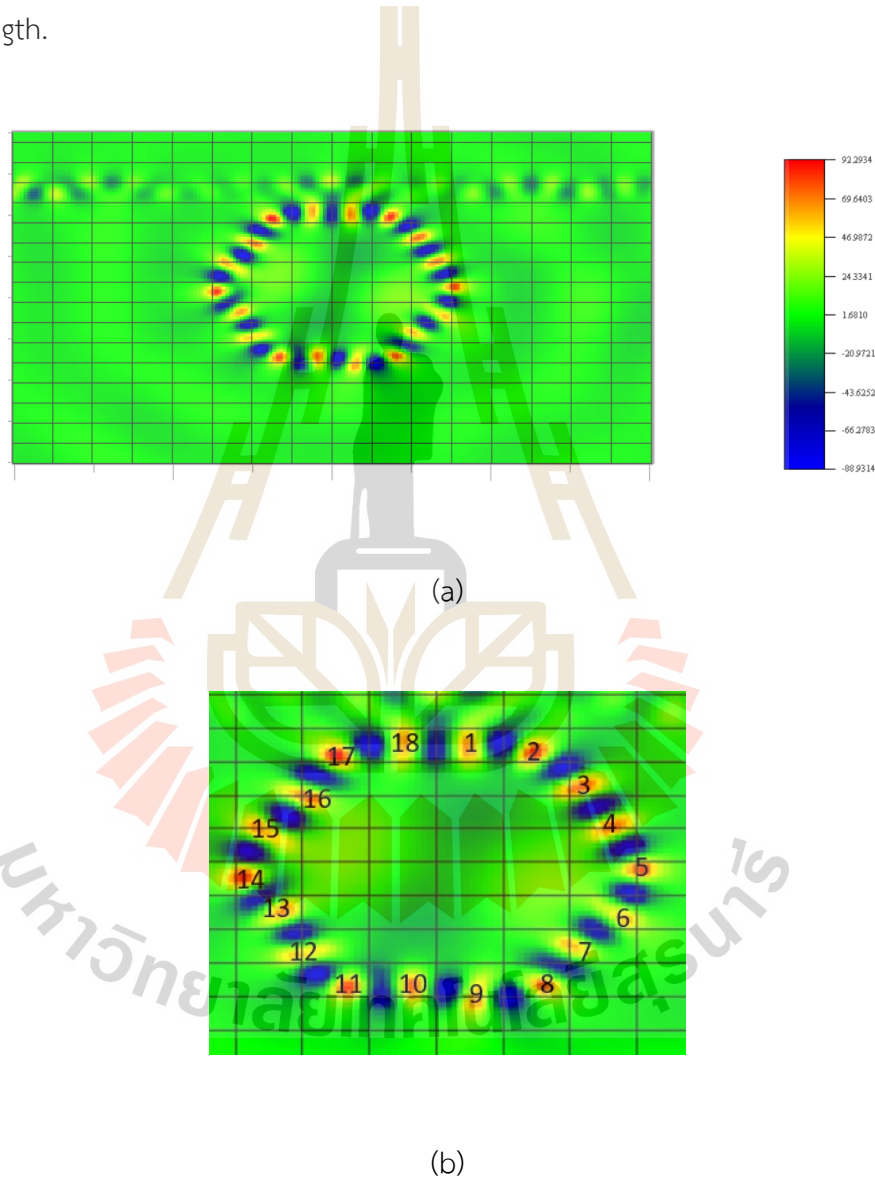


Figure 4.6 The simulated result of Silicon ring resonators with single linear waveguide

- (a) Light propagation
- (b) Number of mode
- (c) 3D of electric field distribution

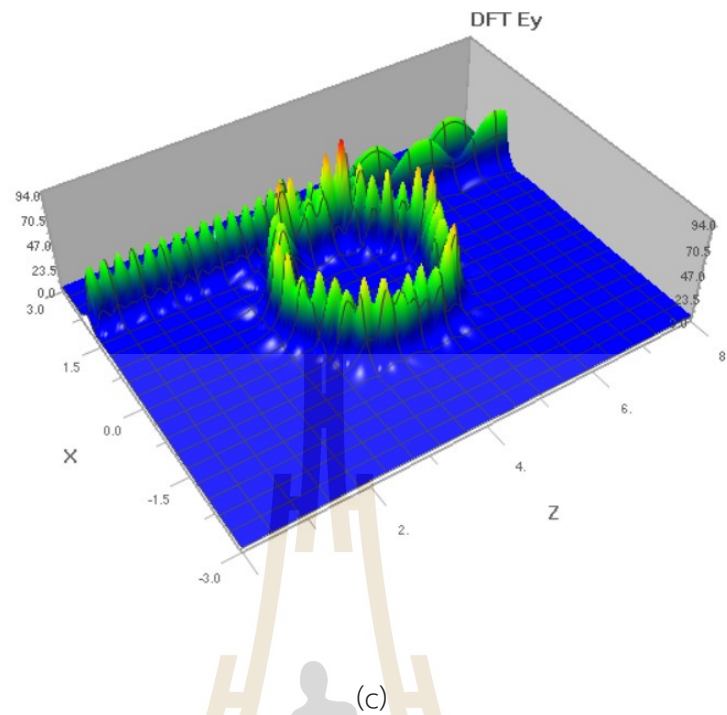


Figure 4.6 The simulated result of Silicon ring resonators with single linear waveguide (continued)

- (a) Light propagation
- (b) Number of mode
- (c) 3D of electric field distribution

Subsequently, the optical intensity at the input port, output port, and within the ring resonator is analyzed in order to evaluate the coupling behavior. In this investigation, the optimized structural parameters obtained from the previous step are retained, while the gap distance between the silicon linear waveguide and the ring resonator is varied systematically. The gap size g is adjusted to 0, 0.1, 0.2, 0.3, 0.4, and 0.5 μm to examine its influence on evanescent coupling efficiency and resonance characteristics. The corresponding simulation results are presented in the following section.

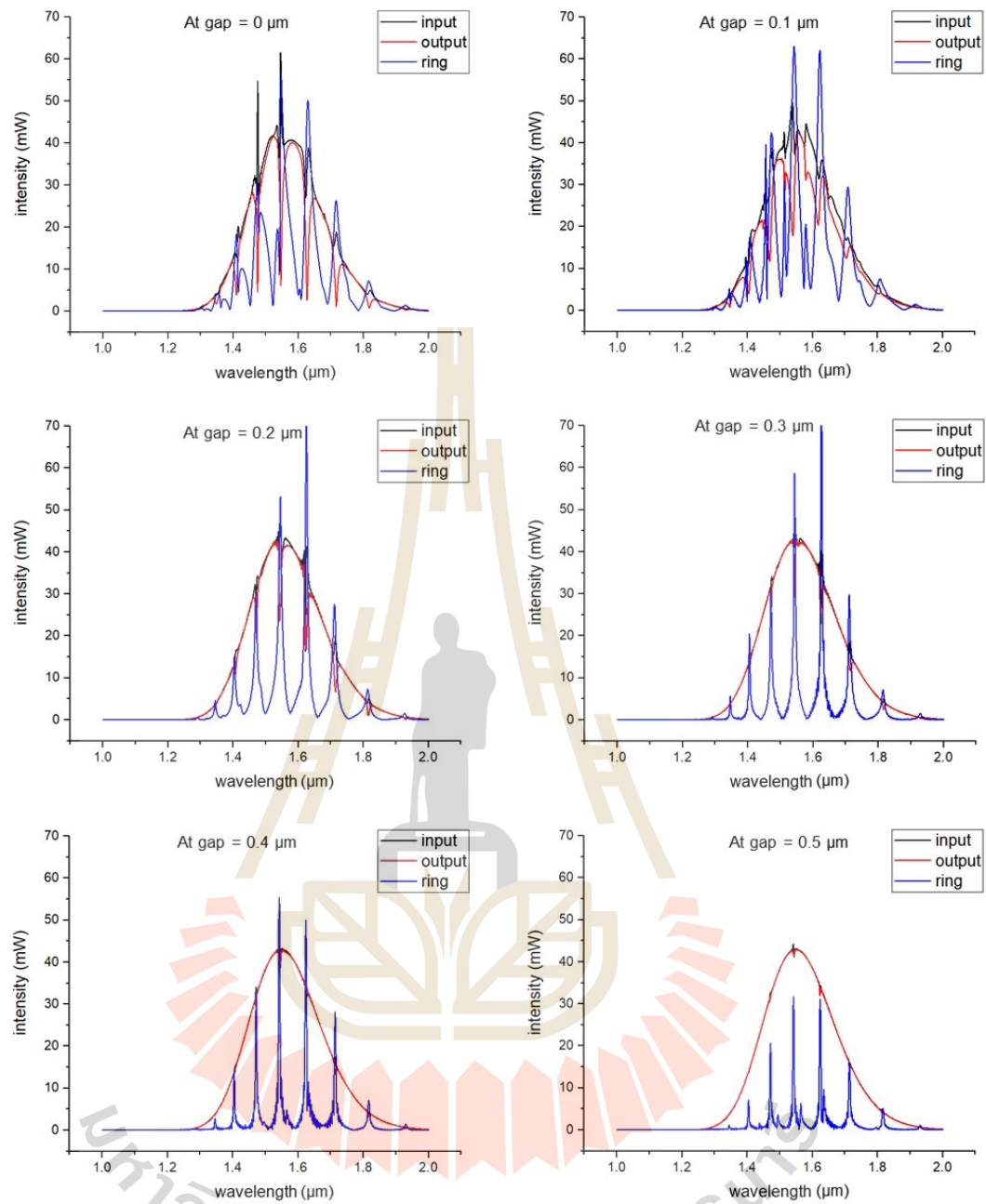


Figure 4.7 The intensity of input port, output port and ring resonator with different gap sizes.

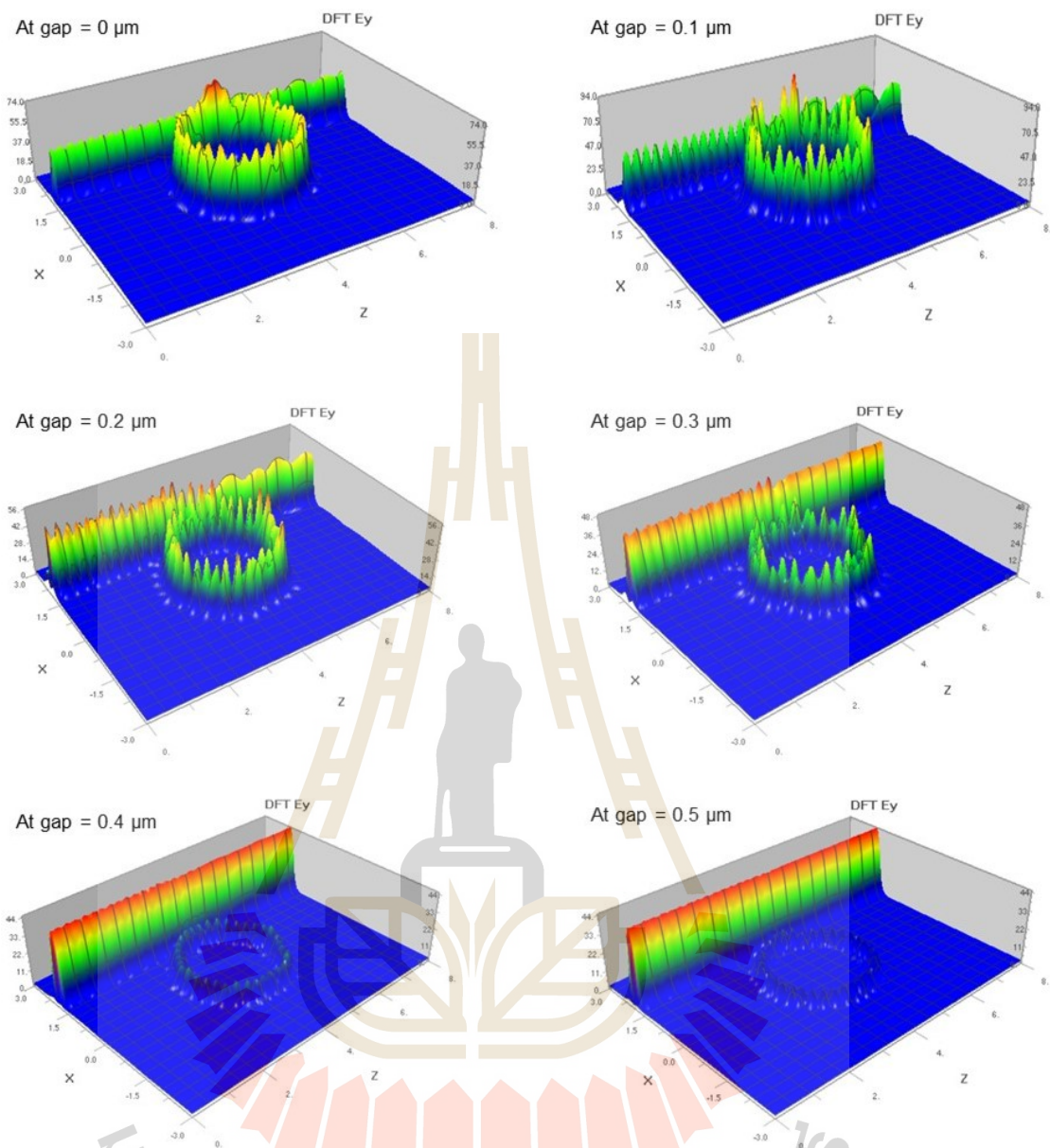


Figure 4.8 The DFT of electric field along Y-axis with different gap sizes.

Figure 4.7 presents the simulated optical intensity at three observation points, namely the input port, output port, and the ring resonator, for six different gap sizes. It can be observed that the input and output port intensities remain nearly constant, with amplitudes in the range of approximately 40–45 mW for all gap variations. In contrast, the intensity within the ring resonator exhibits a strong dependence on the gap distance. The most pronounced resonance enhancement occurs at a gap size of 0.1 μm , indicating optimal evanescent coupling under near-critical coupling conditions. As the gap increases beyond this value, the coupling

efficiency decreases, resulting in reduced circulating intensity within the ring. In the case of zero gap, the response inside the ring is higher than that obtained for gap sizes between 0.2 and 0.5 μm , since the optical field can directly enter the ring without relying solely on evanescent coupling. However, the zero-gap condition still produces a lower intensity compared to the optimized 0.1 μm gap, suggesting that a small but finite separation provides better phase matching and controlled coupling. This observation is consistent with the discrete Fourier transform (DFT) analysis of the electric field along the Y-axis (E_y), as illustrated in Figure 4.8. In this figure, the X-axis represents the transverse width direction, while the Z-axis corresponds to the propagation direction of light. The influence of gap variation on the transmission spectra is analyzed in the subsequent section.

The study of nonlinear phenomena in fiber ring resonators plays an important role in optical communication. The nonlinearity leads to a decrease in the line width and absorption. Therefore, these phenomena assist the generation of slow light in microring resonator. For simplification of the equation, the output field at steady state is given as (Afroozeh, 2018); $y_1 = \sqrt{1 - \kappa_1}$, $x_1 = \sqrt{1 - \gamma_1}$, $\tau = \exp(-\alpha L/2)$ and $\phi = kLn_0 + kLn_2|E_1|^2$. Here α and γ are the absorption coefficient and fractional coupling intensity loss, respectively. L is the circumference of each ring, n_2 is the nonlinear refractive index, n_0 is the linear refractive index and ϕ is the combine of linear and nonlinear phase shift. κ_1 is the coupling coefficient and $k = 2\pi/\lambda$ is the wave propagation number in a vacuum. τ is a one roundtrip loss.

The transfer function of this configuration is derived by the scattering matrix method (Capmany & Muriel, 1990; Choi et al., 2002). The light in the ring resonator filter is incorporated in the attenuation constant, and the interaction can be described. The output electric field can be calculated via scattering matrix method. The proposed system decomposes the transform-limited laser pulse into the spectral domain and modified the pulse spectrum using a one-dimensional fixed or programmable spatial mask or hologram. The modified temporal spectrums are then recombined into the time domain. The input optical field in the form of Gaussian pulse can be expressed (Choi et al., 2002) as

$$E_{in} = A_i \exp \left[\frac{z}{2L_D} - i\omega_0 t \right] \quad (4.4)$$

Where the amplitude of optical field is represented by A_i . The propagation distance is demonstrated by z . The propagation time for Gaussian pulse

moves at the group velocity in a frame is $T = t - \beta_1 \times z$. Here, t is the Gaussian phase shift time, ω_0 and is the frequency shift of the Gaussian. $L_d = T_0^2 / \beta_2$ represents the dispersion length of the Gaussian pulse, where T_0 shows Gaussian pulse propagation time at the initial input. The coefficients of the linear and the second-order terms of the Taylor's expansion of the propagation constant are β_1 and β_2 , respectively.

In this case, Gaussian beam has been used as an input pulse inside to ring resonators. The output is given as:

$$E_{out} = E_{in} x_1 y_1 + i \sqrt{\kappa_1} x_1 \tau_1 e^{-i\phi_1} \left(\frac{i \sqrt{\kappa_1} x_1 E_{in}}{1 - x_1 y_1 \tau_1 e^{-i\phi_1}} \right) \quad (4.5)$$

The transmission intensity output is simulated using the MATLAB programming by iterative and numerical methods. Generally, the transmission in the single ring resonator system can be calculated as Equation 4.6 and shows in Figure 4.9.

$$T = \frac{E_{out}}{E_{in}} = \frac{x_1 y_1 - x_1^2 \tau e^{-i\phi_1}}{1 - x_1 y_1 \tau e^{-i\phi_1}} \quad (4.6)$$

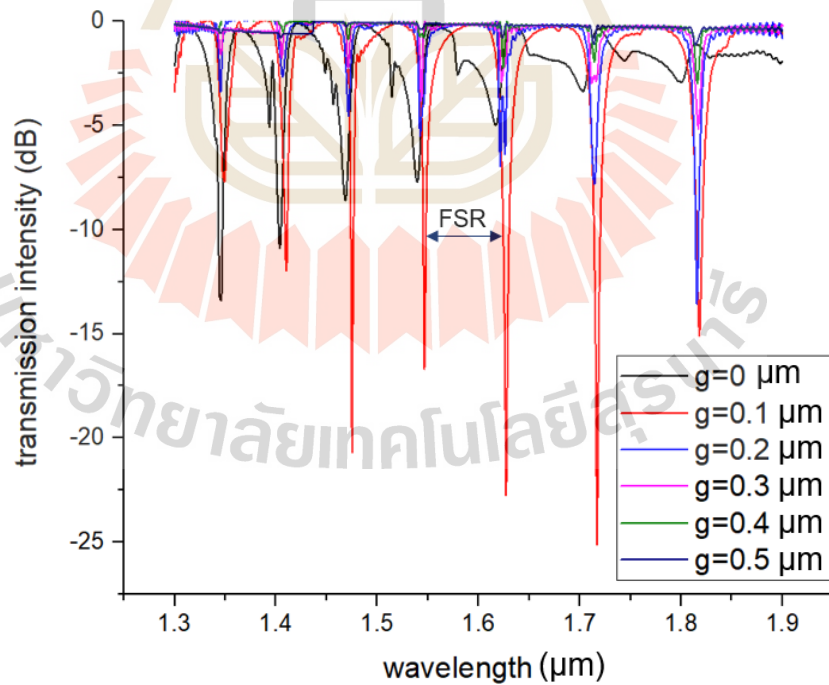


Figure 4.9 The transmission spectra with different gap sizes.

Figure 4.9 shows the broader spectrum of transmission on a log scale. The free spectral range (FSR) of the microring resonator is the spacing in optical frequency or wavelength between two successive reflected or transmitted optical intensity maxima or minima of an interferometer or diffractive optical element. The FSR is dependent on the parameters of a ring resonator as $FSR = \lambda_0^2 / n_g L$. Here λ_0 , n_g and L are the resonance wavelength, the group index and the physical length of the ring waveguide, respectively.

In many practical applications, a relatively large FSR is desirable because the operational wavelength range is typically limited to a single FSR interval. For example, in ring-resonator-based optical sensing systems, the measurable refractive index variation must remain within one FSR to avoid ambiguity in resonance tracking. If the resonance shift caused by index variation exceeds one FSR, the system may misinterpret the shifted peak as an adjacent resonance order, resulting in measurement errors or loss of detection accuracy. Therefore, careful design of the ring dimensions is essential to ensure an appropriate FSR for the intended sensing or filtering application.

4.2.3 Add-Drop Ring Resonator

To enhance spectral selectivity and enable controlled wavelength routing, the single-ring configuration is extended to an add-drop ring resonator by introducing a second linear waveguide coupled to the ring, as illustrated in Figure 4.10. In this structure, the upper waveguide functions as the input-through port, while the lower waveguide serves as the drop-add port. The presence of two coupling regions allows optical energy to be selectively transferred between waveguides at resonance wavelengths.

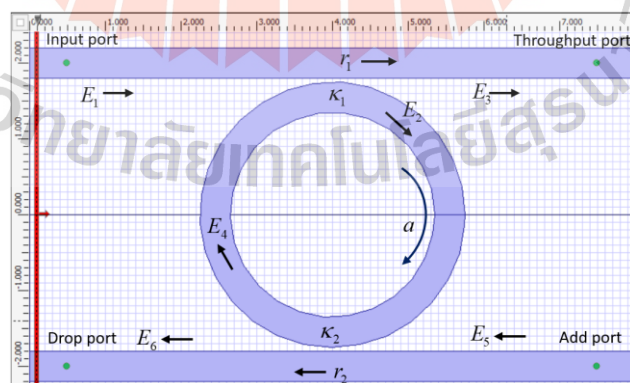


Figure 4.10 The 2D structure of Add-Drop Ring Resonator.

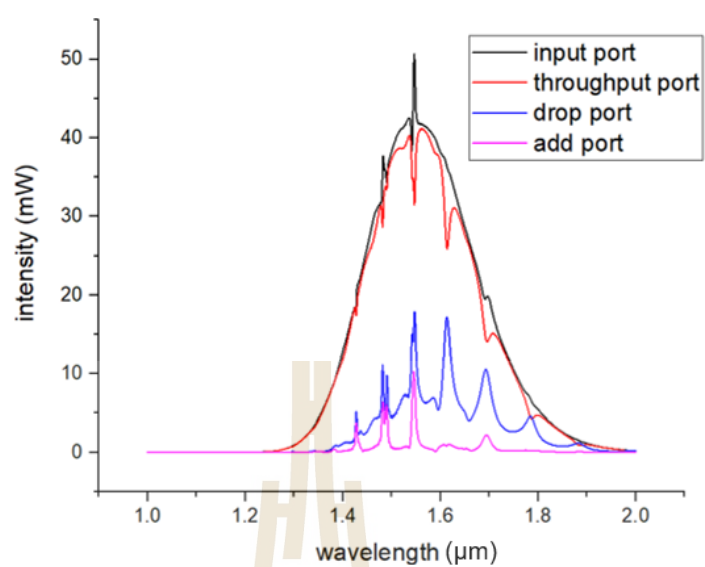
When a continuous-wave optical signal is launched into the input port, part of the field remains in the bus waveguide and exits through the throughput port. At specific resonance wavelengths satisfying the roundtrip phase condition, constructive interference occurs within the ring cavity, leading to strong circulating fields. Under these conditions, the resonant energy is efficiently coupled to the second waveguide and extracted through the drop port. The transmission characteristics of the throughput and drop ports can be derived under steady-state operation by applying field continuity and coupling relations, as expressed in Equations (4.7) and (4.8).

$$T_p = \frac{I_{\text{pass}}}{I_{\text{input}}} = \frac{r_2^2 a^2 - 2r_1 r_2 a \cos \phi + r_1^2}{1 - 2r_1 r_2 a \cos \phi + (r_1 r_2 a)^2} \quad (4.7)$$

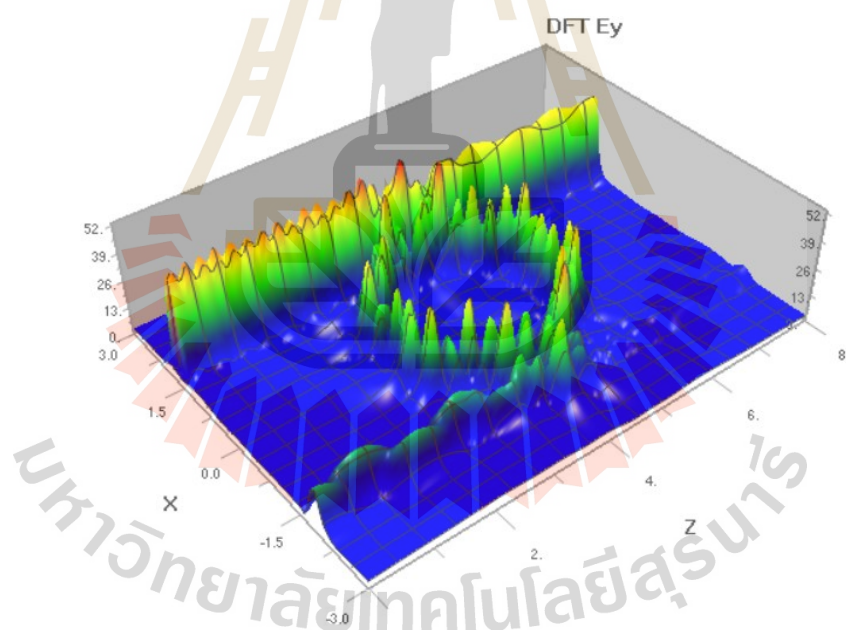
$$T_p = \frac{I_{\text{drop}}}{I_{\text{input}}} = \frac{(1 - r_1^2)(1 - r_2^2)a}{1 - 2r_1 r_2 a \cos \phi + (r_1 r_2 a)^2} \quad (4.8)$$

If the attenuation is negligible ($a \approx 1$), critical coupling or $\kappa_1 = \kappa_2$ occurs at symmetric coupling. For a lossy resonator, critical coupling occurs when the losses match the coupling as $r_2 a = r_1$.

The coupling condition plays a crucial role in determining the energy distribution among the ports. In the ideal lossless case, critical coupling occurs when the coupling coefficient equals the intrinsic roundtrip loss of the ring, resulting in maximum power transfer to the drop port and minimum transmission at the throughput port. In practical structures where material and scattering losses are present, critical coupling is achieved when the external coupling loss matches the internal cavity loss. Simulation results of the add-drop configuration are shown in Figure 4.11. The power intensity distribution in Figure 4.11(a) indicates that a portion of the optical signal is successfully transferred from the upper waveguide to the lower waveguide at resonance. However, the drop and add port intensities are initially relatively small compared to the input and throughput ports, suggesting suboptimal coupling conditions. This behavior is further confirmed by the electric-field distribution and transmission spectra shown in Figures 4.11(b) and 4.11(c), respectively.



(a)



(b)

Figure 4.11 The simulate result of Add-Drop Ring Resonator

(a) power intensity of four ports

(b) DFT of electric field along Y-axis

(c) transmission spectra of throughput and drop port.

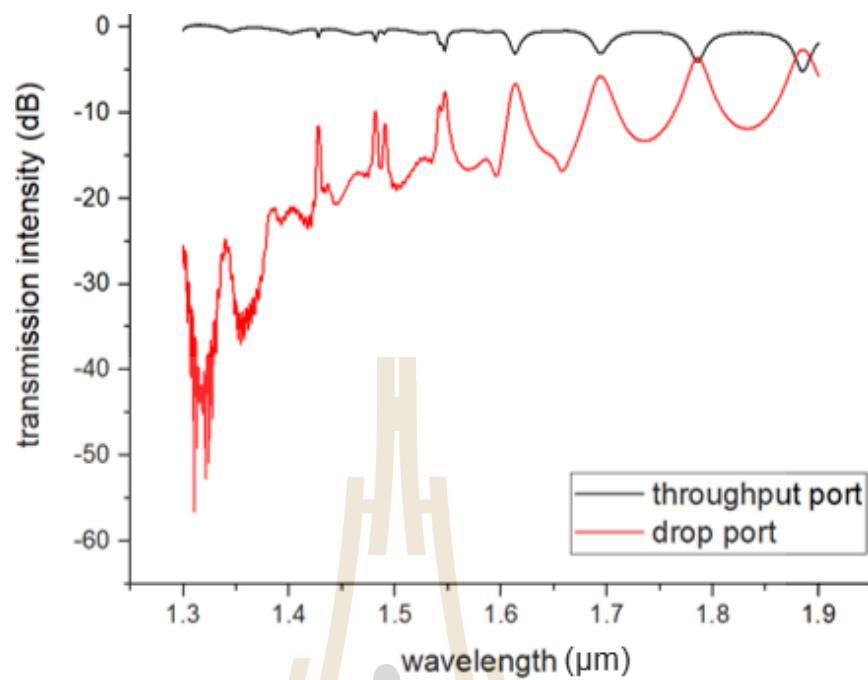


Figure 4.11 The simulate result of Add-Drop Ring Resonator (continued)

- (a) power intensity of four ports
- (b) DFT of electric field along Y-axis
- (c) transmission spectra of throughput and drop port.

Figure 4.11(a) shows the power intensity of input, throughput, drop and add port which indicate that the light beam can coupling from upper linear waveguide to another one. However, the power intensity of drop and add port is very small while compare with input and throughput port which will be consistent with Figure 4.11(b) and directly effect to the unmatching result at the resonance wavelength as shown in Figure 4.11(c).

To improve performance, key structural parameters are systematically tuned. The influence of gap size, linear waveguide width, and ring width on the drop-port intensity is examined, as shown in Figures 4.12–4.14. By optimizing these parameters, stronger resonance enhancement and improved power extraction at the drop port are achieved. The optimized dimensions are summarized in Table 4.2, and the corresponding improved response is presented in Figure 4.15. The optimized configuration demonstrates enhanced drop-port intensity at the resonance wavelength

of 1.55 μm , improved spectral symmetry, and clearer free spectral range (FSR) characteristics.

1) The effect of gap size tuning is investigated by varying the separation distance between the waveguide and the ring at $g=0, 0.1, 0.2$, and $0.3 \mu\text{m}$. To facilitate a clear comparison of coupling efficiency and resonance enhancement, the analysis focuses primarily on the add-port response, as illustrated in Figure 4.12. This approach allows direct evaluation of how the gap distance influences power transfer and resonance strength at the selected operating wavelength.

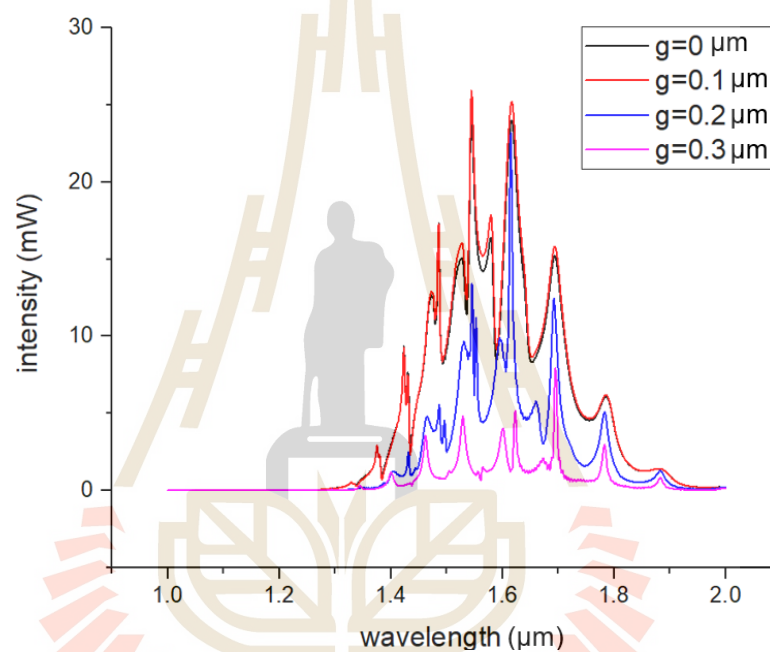


Figure 4.12 The drop port power intensity of gap size varying.

2) The influence of the linear waveguide width is examined by varying w_w at 0.30, 0.35, 0.40, 0.45, and 0.50 μm . This parameter directly affects mode confinement, effective refractive index, and coupling efficiency between the bus waveguide and the ring resonator. For clarity and consistent comparison, the analysis focuses on the add-port response, as presented in Figure 4.13. This enables clear evaluation of how variations in waveguide width impact resonance enhancement and power extraction at the operating wavelength.

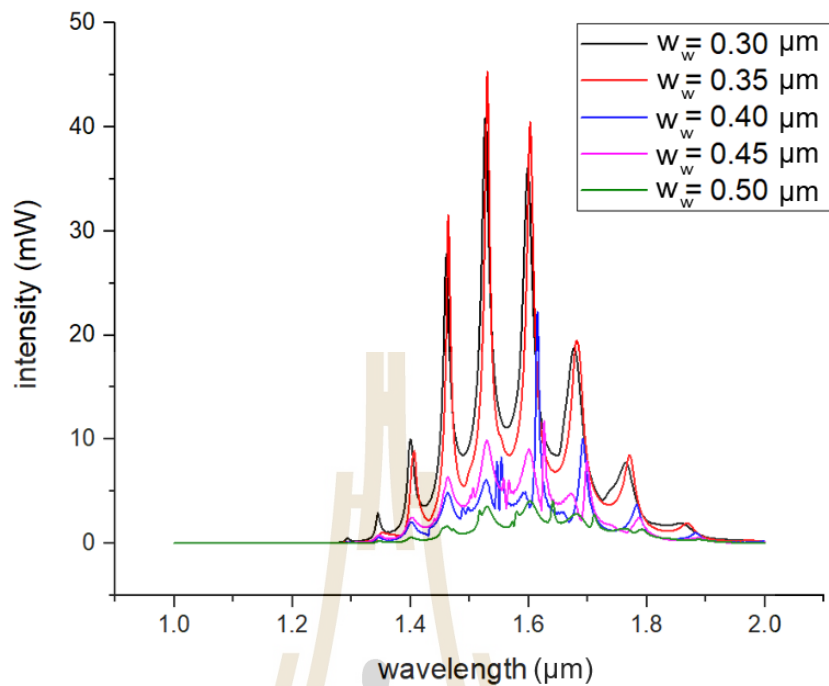


Figure 4.13 The drop port power intensity of linear waveguide width varying.

3) The effect of ring width tuning is investigated by varying the ring width w_r at 0.30, 0.35, 0.40, 0.45, and 0.50 μm . The ring width plays a significant role in determining mode confinement within the resonator, effective refractive index, and the overall resonance characteristics. Variations in this parameter directly influence the circulating field distribution and coupling interaction with the bus waveguides. For consistent comparison and clearer interpretation of performance variation, the analysis focuses on the add-port response, as shown in Figure 4.14. This allows direct assessment of how changes in ring width affect resonance enhancement and power extraction at the operating wavelength.

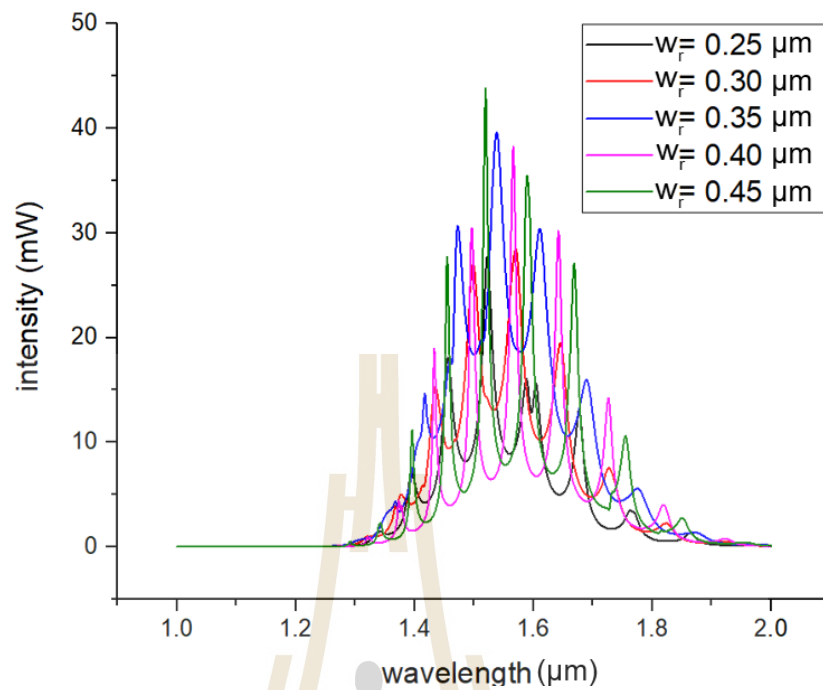


Figure 4.14 The drop port power intensity of ring width varying.

Ultimately, based on the observed trends from the systematic tuning of the three key structural parameters optimal dimensions are determined and summarized in Table 4.2. The corresponding optimized performance is presented in Figure 4.15, which demonstrates the improved resonance response and enhanced drop-port power intensity under the selected parameter configuration.

Table 4.2 The dimension of silicon ring resonators with double linear waveguide structure

Parameters	Dimension	Unit
length of silicon linear waveguide	8	μm
width of silicon linear waveguide	0.35	μm
thickness of silicon linear waveguide	0.5	μm
radius of silicon ring	1.3	μm
width of silicon ring	0.35	μm
thickness silicon ring	0.5	μm
gap size	0.1	μm
silicon refractive index	3.42	-
silicon non-linear refractive index	1.3×10^{-13}	m^2/W

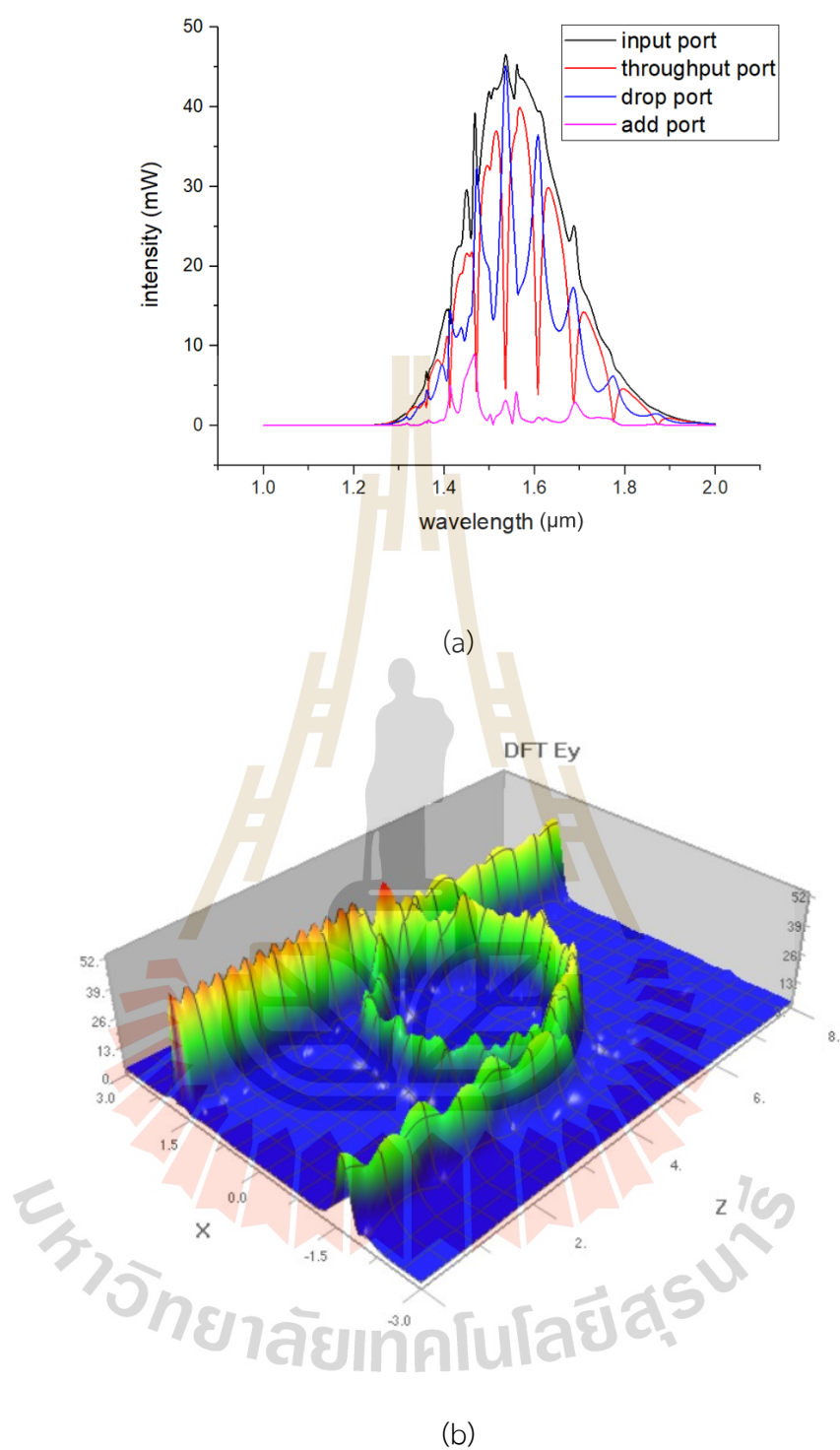
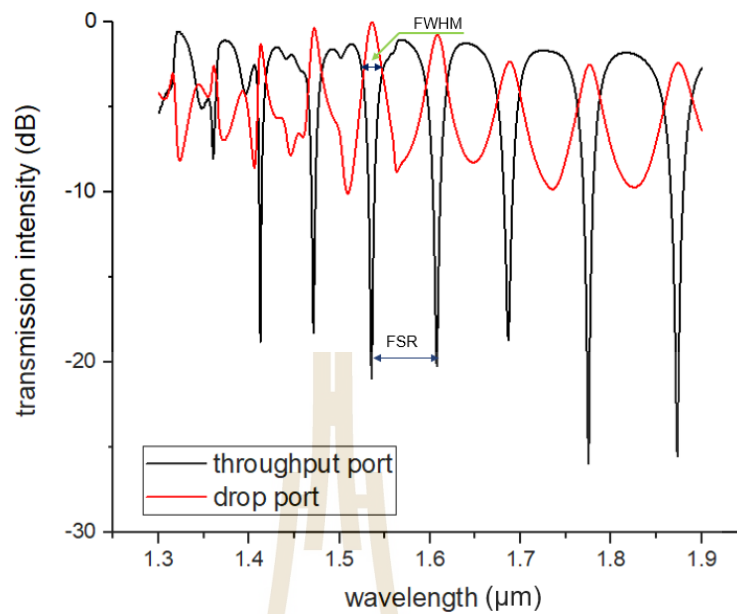


Figure 4.15 The response of tuning ring resonators with double linear waveguide

(a) power intensity of four ports

(b) DFT of electric field along Y-axis

(c) transmission spectra of throughput and drop port.



(c)

Figure 4.15 The response of tuning ring resonators with double linear waveguide (continued)

- (a) power intensity of four ports
- (b) DFT of electric field along Y-axis
- (c) transmission spectra of throughput and drop port.

Figure 4.15 presents the optimized simulation results obtained after parameter tuning. At the resonance wavelength of $1.55 \mu\text{m}$, the drop-port power intensity is significantly enhanced compared to the previous configurations. As shown in Figure 4.15(a), the power distribution among the four ports demonstrates improved energy transfer to the drop port under optimized coupling conditions.

The DFT analysis of the electric field along the Y-axis, illustrated in Figure 4.15(b), confirms that a portion of the optical field is effectively redirected into the drop port, while the amplitude of the throughput port approaches equilibrium. This indicates improved coupling balance and more efficient resonance-assisted power routing. Furthermore, the transmission spectrum plotted on a logarithmic scale in Figure 4.15(c) clearly reveals the free spectral range (FSR) and the full width at half maximum (FWHM at -3 dB), demonstrating enhanced spectral selectivity and resonance sharpness.

These results indicate that the optimized add-drop ring resonator configuration is well suited for wavelength multiplexing, demultiplexing, and modulation applications. Nevertheless, further improvement in resonance control and modal confinement can be achieved by incorporating two additional side rings adjacent to the main ring. This extended configuration, known as the Panda-ring resonator, is discussed in the following subsection.

4.2.4 Panda-ring resonator

To further enhance resonance control and modal confinement, the add-drop ring configuration is extended to a Panda-ring resonator by incorporating two auxiliary side rings coupled to the central ring, as illustrated in Figure 4.16. This configuration introduces additional coupling interfaces, enabling multi-resonant interaction and improved control over whispering-gallery-mode (WGM) localization. In the Panda-ring structure, the central ring functions as the primary resonant cavity, while the two smaller side rings act as auxiliary modulators that influence phase accumulation and field distribution within the system. Optical energy launched from the input port propagates along the bus waveguide and couples into the central ring through evanescent interaction. The presence of the side rings introduces additional coupling paths, which radius R . Rings 2, 3 whose radius being R_R and R_L , are side coupled to central ring. The coupling coefficients between the central ring and bus waveguides at the top and bottom are κ_1, κ_2 respectively. The coupling coefficient between central ring and ring 2, ring 3 are κ_3, κ_4 respectively.

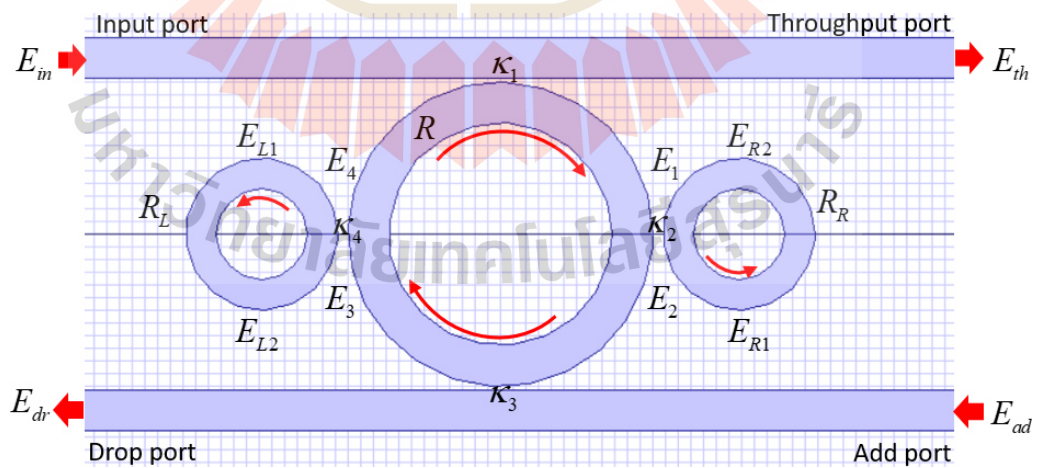


Figure 4.16 Functional schematic of Panda-ring resonator.

In Figure 4.16, the optical excitation is introduced into the system through the input port and is represented by the input electric field (E_{in}). The propagating field along the Z-axis can be expressed as $E_{in} = E_z = E_0 e^{-i(k_z z - \omega t)}$, where E_0 denotes the real amplitude of the electric field, k_z is the wave number in the direction of propagation (Z-axis) and ω is the angular frequency, where $\phi = \omega t$, t represents the temporal evolution of the wave. Within the Panda-ring configuration, four coupling nodes are formed due to the interaction between the central ring, the side rings, and the bus waveguides. The electric field at each node is governed by the coupling relations and roundtrip phase conditions of the resonator system. The node signals can therefore be expressed using the following field equations.

$$E_{dr} = \sqrt{1-\gamma_3} \left(\sqrt{1-\kappa_3} E_{ad} + i\sqrt{\kappa_3} E_{12} e^{-\frac{\alpha L_D}{2} - ik_n \frac{L_D}{4}} \right) \quad (4.9)$$

$$E_{th} = \sqrt{1-\gamma_1} \left(\sqrt{1-\kappa_1} E_{in} + i\sqrt{\kappa_1} E_{14} e^{-\frac{\alpha L_D}{2} - ik_n \frac{L_D}{4}} \right) \quad (4.10)$$

$$E_{ad} = \sqrt{1-\gamma_3} \left(\sqrt{1-\kappa_3} E_{dr}^* + i\sqrt{\kappa_3} E_{12} e^{-\frac{\alpha L_D}{2} - ik_n \frac{L_D}{4}} \right) \quad (4.10)$$

The silicon microring conjugate mirror (MCM) corresponding to each required node can be formulated based on the field relationships within the coupled resonator system. In this formulation $E_{dr}^* = -nE_{dr}$. n represents the reflection ratio; E_{ad} denotes the electric field at the add port output. The field components E_{12} , E_{14} , E_{22} and E_{24} correspond to the electric fields circulating at different coupling interfaces within the resonator structure. The parameter γ represents the intensity insertion loss coefficient of the 3 dB couplers, while κ denotes the coupling constant between the interacting waveguides and rings. The term α accounts for the attenuation loss of light propagating along the waveguide $k_n = (2\pi/\lambda)n_{eff}$, and L_D corresponds to the physical circumference of the central ring, which determines the roundtrip phase accumulation. Using these field relationships and parameters, the complete Panda-ring resonator structure is numerically simulated based on the optimized dimensional values summarized in the following table.

Table 4.3 The dimension of Panda-ring resonators structure

Parameters	Dimension	Unit
length of silicon linear waveguide	10	μm
width of silicon linear waveguide	0.3	μm
thickness of silicon linear waveguide	0.5	μm
radius of center ring	1.55	μm
width of center ring	0.3	μm
thickness center ring	0.5	μm
radius of both small ring	0.88	μm
width of center ring	0.3	μm
thickness center ring	0.5	μm
gap size	0.05	μm
silicon refractive index	3.42	-
silicon non-linear refractive index	1.3×10^{-13}	m^2/W

In this application, the primary objective is to generate a stable and well-confined whispering-gallery mode (WGM) within the resonator structure. The WGM can be effectively controlled by adjusting the parameters of the two side rings, which influence the coupling strength and phase accumulation within the Panda-ring configuration. By carefully tuning these side-ring parameters, enhanced energy localization can be achieved along the circular boundary of the central ring. The formation of the WGM is associated with the constructive interference of light circulating along a closed-loop trajectory within the resonator. This circular propagation allows the optical field to remain confined through total internal reflection, while evanescent tunneling between adjacent rings enables controlled energy transfer and redistribution within the system. As a result, optical energy is accumulated and localized at specific positions inside the resonator cavity.

The simulated field distribution demonstrating WGM generation is presented in Figure 4.17. Furthermore, Figure 4.18 illustrates the power intensity measured at five observation points, confirming the enhanced confinement and controlled energy distribution achieved in the Panda-ring resonator.

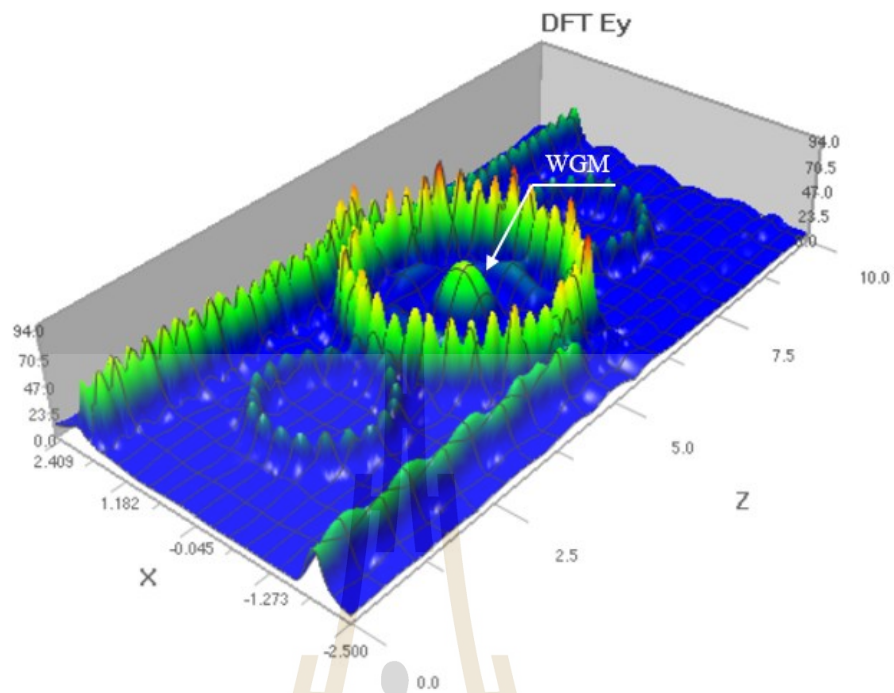


Figure 4.17 Result of controlling the two sides ring to generate WGM.

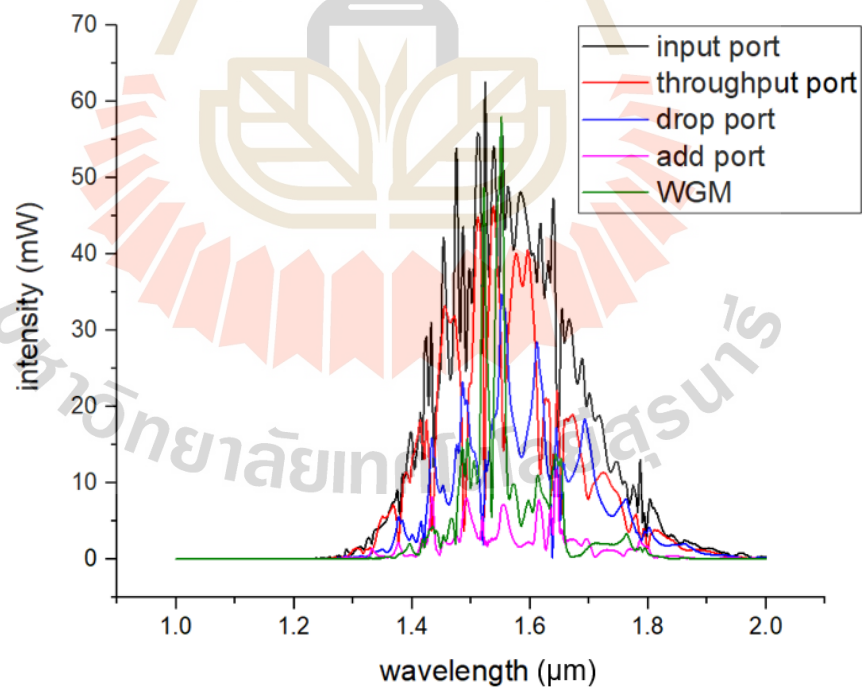


Figure 4.18 The power intensity of observation points on Panda-ring resonator circuit.

For clearer interpretation of the results, the responses shown in Figure 4.18 are separated and normalized with respect to the input port intensity. The power variations at the throughput port, drop port, add port, and the generated WGM output are individually presented in Figure 4.19. This separation enables more precise comparison of energy redistribution among the ports and provides clearer insight into the resonance enhancement behavior within the Panda-ring resonator.

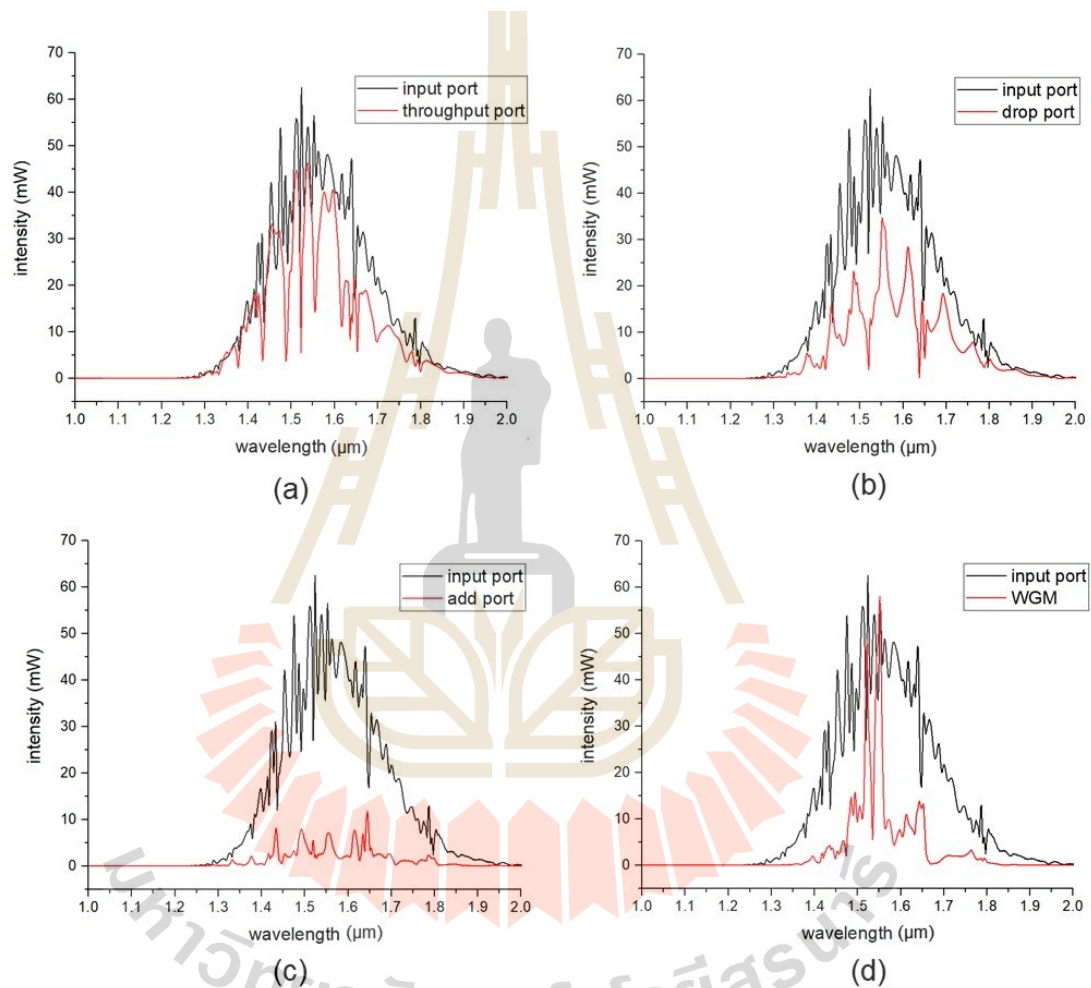


Figure 4.19 The power intensity with respect to the input port

- (a) throughput port
- (b) drop port
- (c) add port
- (d) WGM

The WGM output can be effectively generated and controlled by the two side rings, which function as nonlinear phase modulators within the Panda-ring configuration. By adjusting the coupling and phase conditions of these side rings, the circulating field intensity and resonance characteristics of the central ring can be precisely tuned. This mechanism enables stable and enhanced whispering-gallery-mode localization inside the resonator. The generated WGM is subsequently directed toward the central island region of the structure, where it serves as a coherent excitation source. In this region, the confined photonic energy interacts with the embedded metallic elements, leading to the generation of plasmonic waves. This WGM-driven plasmon excitation forms the fundamental operating principle of the proposed plasmonic nanoantenna, which is investigated in the next section.

4.3 Plasmonic nanoantenna by using Panda-ring resonator circuit

After the whispering-gallery mode (WGM) is successfully generated and stabilized through control of the two side rings, the confined optical energy is directed toward the central island region of the structure. This localized WGM field serves as the excitation source for plasmonic wave generation, enabling the device to function as a nanoantenna. At the nanoscale, plasmonic waves arise from the interaction between incident electromagnetic radiation and the collective oscillation of free electrons in plasmonic materials such as gold, silver, or graphene. When the confined photonic energy of the WGM couples to a metallic structure, surface plasmon polaritons (SPPs) can be excited at the metal–dielectric interface. These SPPs enable strong field localization and facilitate the conversion of guided photonic energy into radiative electromagnetic waves.

To realize this mechanism, a gold grating is integrated onto the silicon cylinder located at the center of the Panda-ring resonator, as illustrated in the following figure. The grating structure enhances momentum matching between the confined WGM and the plasmonic modes, thereby promoting efficient plasmon excitation and radiation coupling. Through this hybrid photonic–plasmonic configuration, the device operates as a WGM-assisted plasmonic nanoantenna.

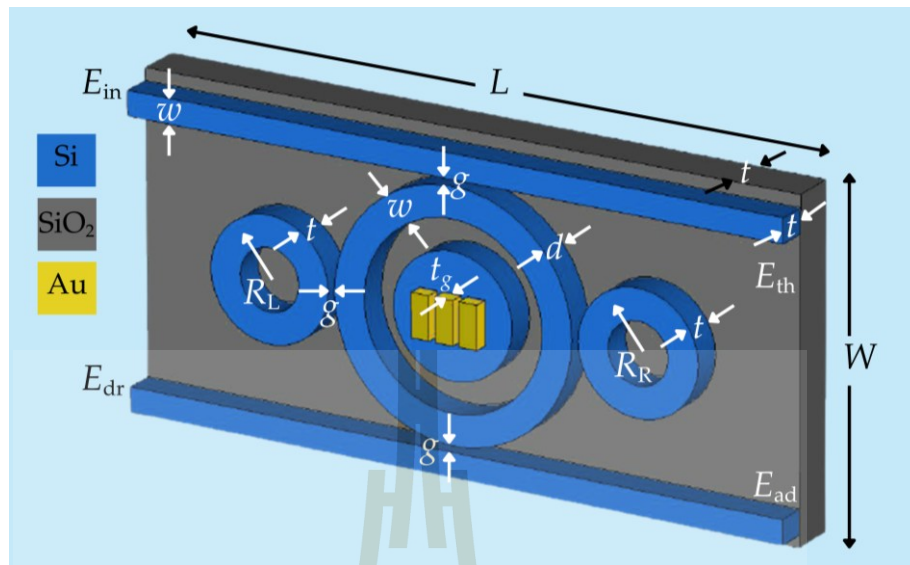


Figure 4.20 The 3D structure of the proposed plasmonic nanoantenna.

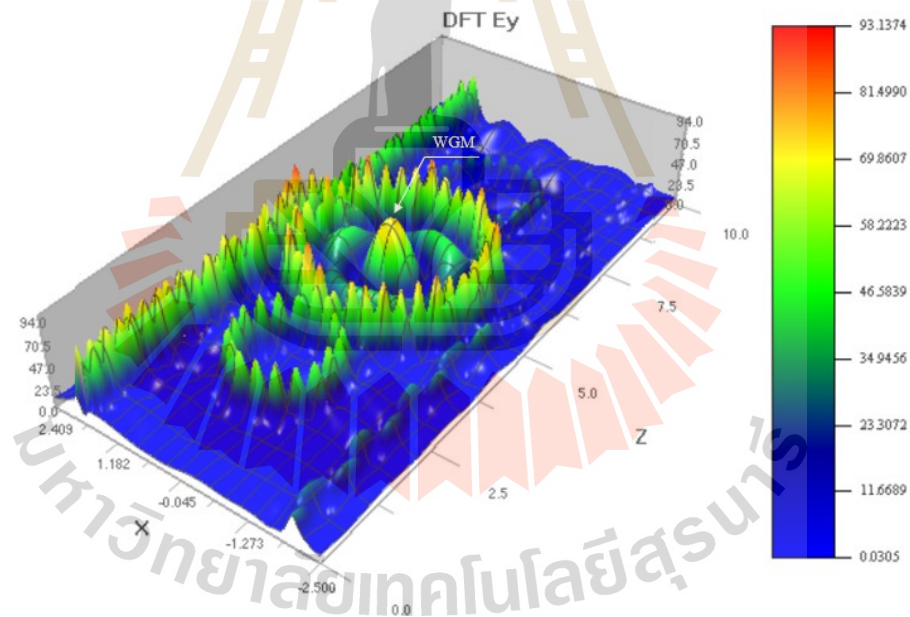


Figure 4.21 The whispering gallery mode of the proposed plasmonic nanoantenna.

A gold grating is integrated onto the silicon cylinder located at the center of the main ring in order to induce surface plasmon polaritons (SPPs). These plasmonic waves arise from the collective oscillation of free electrons at the metal–dielectric interface and resonate at frequencies close to the plasma frequency of the metallic

material. The efficiency of plasmon excitation and coupling strongly depends on the geometrical parameters of the nanograting. In particular, the grating period determines the Bragg wavelength, which can be expressed as $\lambda_B = 2n_e\Lambda$ where n_e is the effective refractive index of the grating mode within the waveguide environment, and Λ is the grating period. Proper selection of the grating dimensions enables momentum matching between the confined whispering-gallery mode (WGM) and the plasmonic modes, thereby enhancing coupling efficiency.

An optical input source with a wavelength of 1.55 μm is launched into the system through the input port. Using the optimized structural parameters summarized in Table 4.4, strong plasmonic polaritons are generated at resonance when the circulating WGM field couples into the gold grating structure. This interaction produces a propagating plasmonic wave corresponding to the Bragg wavelength at the central region of the device.

The plasmonic nanoantenna operates through the radiation of oscillating dipoles formed by the excited polariton waves. In addition to the radiative behavior at the central island, the system maintains conventional photonic outputs at the throughput and drop ports, enabling simultaneous multiplexing and demultiplexing functionality. For numerical implementation, the OptiFDTD 32-bit version 12.0 software is employed to simulate the photonic confinement and WGM formation within the resonator. Light is trapped in the central ring at the designed resonance wavelength. The spatial grid resolution is set to 0.045 μm in both the transverse and longitudinal directions to ensure accurate field representation and stable numerical convergence.

Figure 4.22 illustrates the procedure used to transfer the whispering gallery mode (WGM)-based excitation signal from the OptiFDTD simulation environment to CST Microwave Studio for plasmonic nanoantenna radiation analysis. In the first step, the WGM signal is generated within the panda-ring resonator structure using the OptiFDTD finite-difference time-domain solver. The time-domain electromagnetic response corresponding to the resonant WGM is monitored at a designated observation region, ensuring that the extracted waveform accurately represents the intrinsic resonant behavior of the photonic structure.

Subsequently, the obtained WGM time-domain signal is exported from OptiFDTD in comma-separated values (CSV) format. This exported dataset preserves the temporal characteristics of the resonant signal and enables seamless interoperability between different simulation platforms. The CSV file is then imported into CST Microwave Studio, where it is defined as a reference excitation signal within the excitation signal library.

Table 4.4 The proposed plasmonic nanoantenna parameters

Parameter	Symbols	Values	Units
Input Power (Gaussian Pulse)	P	10	mW
Si-linear waveguide length	L	16	μm
Si center ring radius	R	1.55	μm
Si small left ring radius	R_L	0.88	μm
Si small right ring radius	R_R	0.88	μm
Gold dielectric constant	ϵ_{gold}	6.9	-
Gold permittivity	ϵ	10.0	-
Gold thickness	d	0.1	
Gold Length	L	0.5	μm
Gold refractive index	n	1.8	-
Coupling Coefficient	κ	0.5	-
Insertion loss	γ	0.1	dB
Refractive Index Si	n_{Si}	3.42	-
Si nonlinear refractive index	n_2	1.3×10^{-13}	m^2/W
Input Light wavelength input port	λ	1.55	μm
Waveguide core effective (Arumona et al., 2020)	A_{eff}	0.3	μm^2
Waveguide loss	α	0.5	dB/cm
Plasma frequency	ω_p	-	rad/s
Electron mass	m	9.1×10^{-31}	kg
Electron Charge	e	1.6×10^{-19}	Coulomb
Permittivity of free space	ϵ_0	8.854×10^{-12}	F/m
Grating period	Λ	0.5, 0.4, 0.3	μm

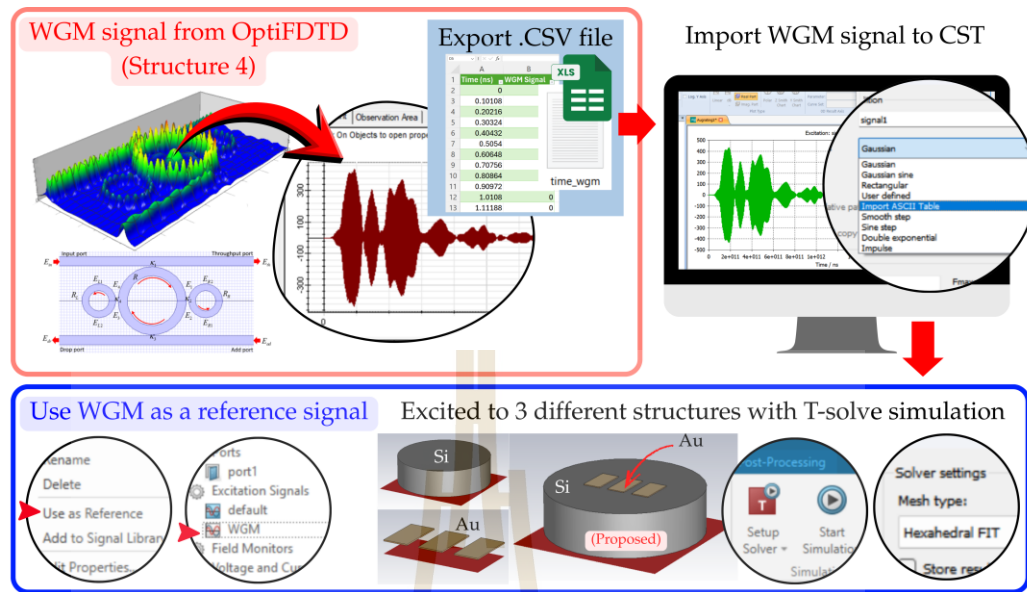


Figure 4.22 Procedure for WGM-based excitation signal transfer from Optiwave FDTD to CST Microwave Studio.

Once imported, the WGM-based excitation is applied to multiple nanoantenna configurations, including silicon-based, gold-assisted, and the proposed hybrid plasmonic nanoantenna structure. The simulations are performed using the time-domain solver (T-solver) in CST Microwave Studio, allowing consistent excitation conditions across all structures. This methodology ensures that differences observed in electromagnetic field distribution, radiation characteristics, directivity, and gain can be attributed to the structural properties of the nanoantenna designs rather than variations in the excitation waveform.

The far-field radiation performance of the proposed plasmonic nanoantenna is evaluated under whispering-gallery-mode (WGM) excitation at an operating frequency of 193.5 THz, corresponding to a free-space wavelength of approximately $1.55 \mu\text{m}$, which is the standard telecommunication wavelength. In order to ensure a fair and physically consistent comparison among different antenna configurations, the same WGM time-domain waveform extracted from the panda-ring resonator is employed as the excitation source in all simulations. Using this unified excitation approach, the radiation characteristics of three different island configurations are systematically investigated: (i) a silicon cylinder only, (ii) a gold grating structure only, and (iii) the proposed hybrid panda-ring plasmonic nanoantenna. By maintaining identical excitation conditions, variations in the resulting radiation patterns, directivity, and gain

can be directly attributed to the structural composition and plasmonic coupling mechanisms of each configuration rather than differences in the excitation signal itself.

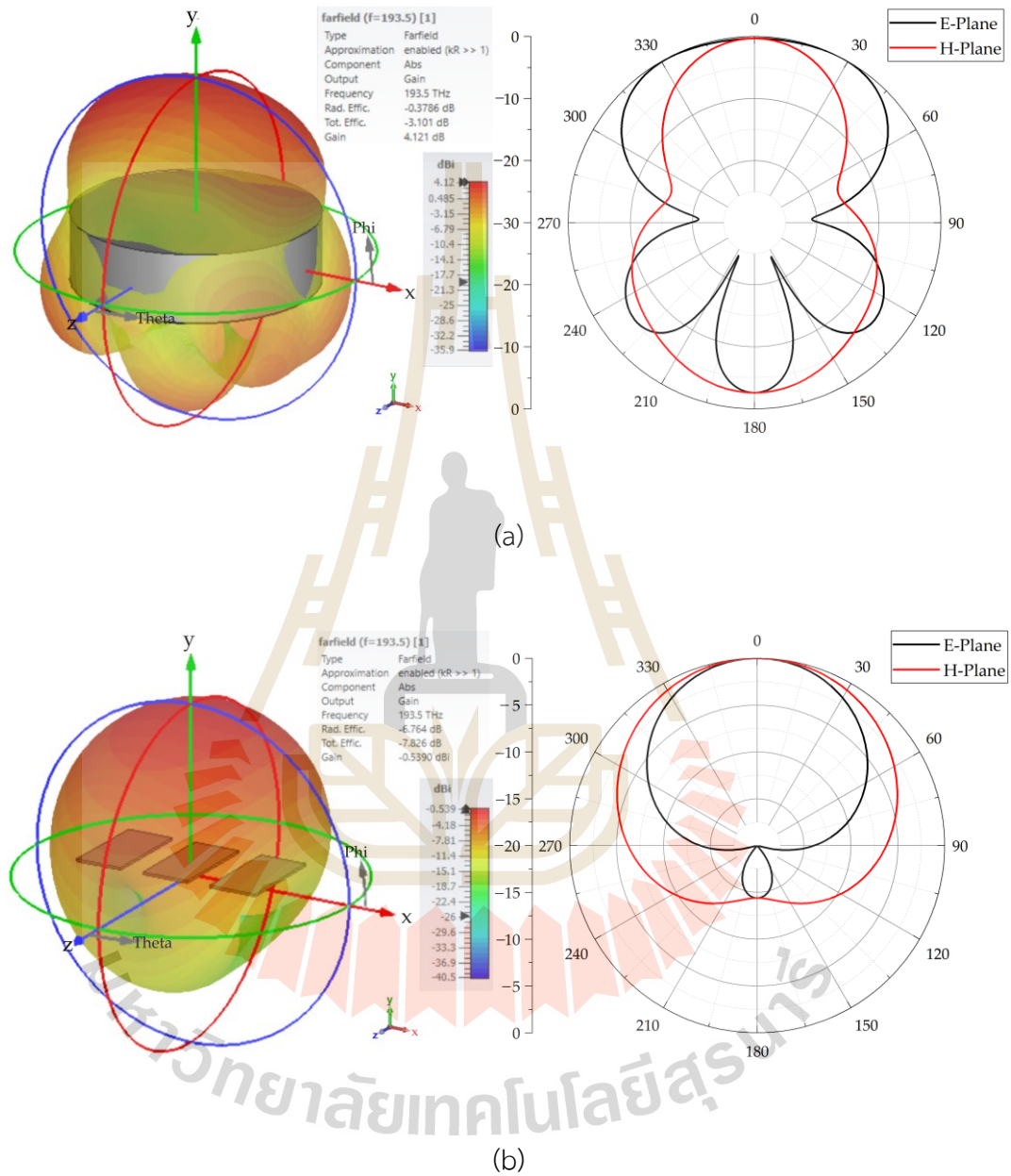


Figure 4.23 Far-field radiation characteristics under identical WGM-driven excitation at 193.5 THz for three different island configurations
 (a) silicon cylinder only
 (b) gold grating only
 (c) the proposed hybrid Panda-ring antenna.

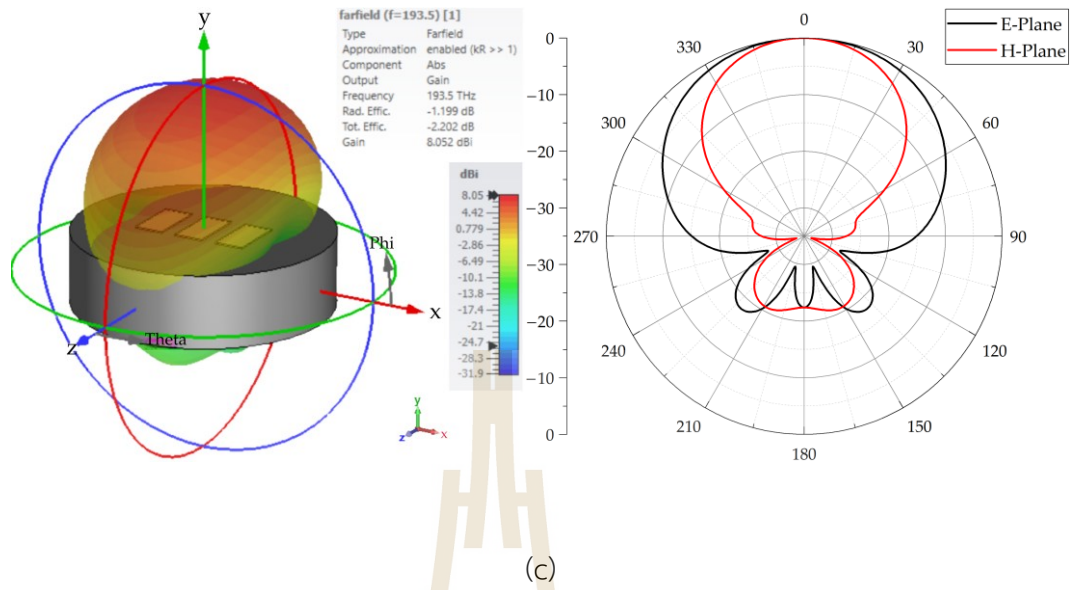


Figure 4.23 Far-field radiation characteristics under identical WGM-driven excitation at 193.5 THz for three different island configurations (continued)

- (a) silicon cylinder only
- (b) gold grating only
- (c) the proposed hybrid Panda-ring antenna.

The far-field radiation performance of the proposed antenna is evaluated under whispering-gallery-mode (WGM) excitation at an operating frequency of 193.5 THz (corresponding to a wavelength of approximately $1.55 \mu\text{m}$). To ensure a fair and physically consistent comparison, the same WGM waveform extracted from the Panda-ring resonator is applied as the excitation source for all investigated island configurations. Three cases are considered: a silicon cylinder only, a gold grating only, and the proposed hybrid Panda-ring antenna. For the silicon-cylinder-only configuration shown in Figure 6a, the realized gain reaches 4.12 dBi, while the radiation efficiency and total efficiency are -0.3786 dB and -3.101 dB, respectively. These results indicate that although the dielectric resonator supports strong WGM confinement with relatively low material loss, a large fraction of the electromagnetic energy remains stored within the high-Q resonator, resulting in limited conversion into free-space radiation and consequently moderate gain.

When the gold-grating-only configuration is considered, as illustrated in Figure 6b, the realized gain decreases to -0.539 dBi, accompanied by a radiation efficiency of -6.764 dB and a total efficiency of -7.826 dB. This configuration is structurally analogous to the plasmonic antenna reported, where a similar grating-based radiating element

was investigated, the reported radiated power is approximately 0.9 mW, corresponding to about -0.5 dB on a logarithmic scale, which shows good quantitative agreement with the gain level obtained in this work. Minor discrepancies can be attributed to differences in the material platform and surrounding dielectric environment, which affect plasmonic confinement, ohmic loss, and impedance matching. Despite these differences, both studies exhibit a cardioid-like radiation pattern in the magnetic-field (H-plane), indicating a common plasmonic radiation mechanism governed by asymmetric surface current distribution along the grating. Nevertheless, in the absence of a coherent photonic energy-feeding mechanism, plasmonic fields remain weakly organized and strongly affected by ohmic dissipation, resulting in limited radiation efficiency and degraded overall performance.

In contrast, the proposed hybrid Panda-ring antenna shown in Figure 6c exhibits a pronounced enhancement in far-field radiation characteristics. The realized gain increases to 8.05 dBi, while the radiation efficiency and total efficiency improve to -1.20 dB and -2.20 dB, respectively. The radiation pattern is dominated by a stable broadside main lobe with improved angular symmetry and controlled sidelobe levels, indicating efficient and directive energy extraction from the resonator into free space. Compared with the silicon-only configuration, the hybrid structure achieves an approximate gain enhancement of 3.9 dB and a total-efficiency improvement of nearly 0.9 dB. Relative to the gold-grating-only case, the gain enhancement exceeds 8.5 dB, accompanied by a total-efficiency improvement of more than 5.6 dB. These results demonstrate that neither dielectric WGM confinement nor plasmonic radiation alone is sufficient to achieve high-performance radiation under WGM excitation. Similar gain enhancement trends have been reported in hybrid plasmonic nanoantenna systems, where the introduction of gold-based plasmonic elements resulted in measurable gain improvement due to enhanced radiation efficiency and effective mode conversion.

The electric-field distributions in Figure 7 provide direct physical insight into these far-field behaviors. Under identical WGM excitation, the silicon-only configuration (Figure 7a) exhibits strong field confinement along the resonator boundary with minimal leakage into free space, explaining its moderate gain and limited total efficiency. For the gold-grating-only case (Figure 7b), localized plasmonic excitation is observed around the metallic elements; however, the field distribution lacks global coherence and is strongly affected by ohmic loss, consistent with the poor radiation efficiency obtained in the far-field analysis.

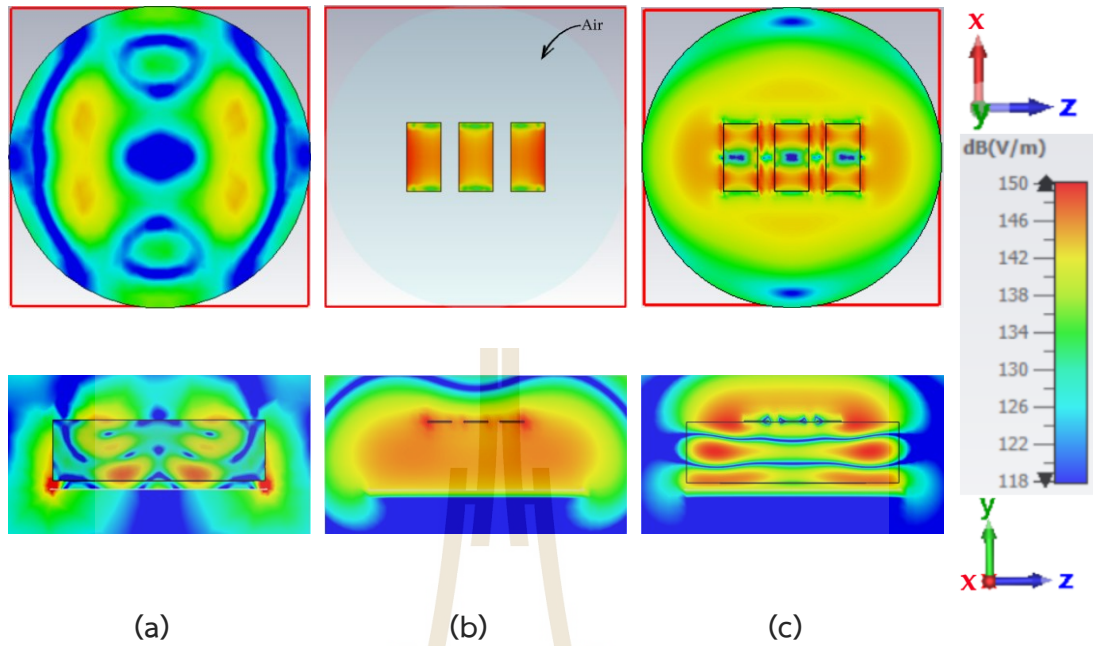


Figure 4.24 Electric-field distribution at 193.5 THz under identical WGM excitation for
 (a) silicon cylinder only
 (b) gold grating only
 (c) the proposed hybrid Panda-ring antenna.

By contrast, the proposed hybrid Panda-ring antenna (Figure 7c) exhibits spatially coherent electric-field localization simultaneously within the dielectric resonator and at the metal–dielectric interface of the embedded gold grating. This redistribution reflects efficient overlap between whispering-gallery modes and surface plasmon polaritons, enabling momentum matching and controlled radiative out-coupling. As a result, resonantly stored energy is efficiently extracted into free space without compromising resonance stability. These observations confirm that the enhanced gain and efficiency originate from the synergistic WGM-assisted plasmonic radiation mechanism, establishing the proposed Panda-ring antenna as a promising platform for Li-Fi transmitters, terahertz wireless links, and integrated photonic–plasmonic communication systems.

CHAPTER VI

THESIS CONCLUSION

5.1 Conclusion

This thesis has presented the design, analysis, and numerical evaluation of a nanoplasmonic antenna based on a panda-ring resonator circuit integrated with a gold grating structure for high-frequency and optical communication applications. The primary objective of the research was to investigate how plasmonic resonance and whispering gallery modes (WGMs) can be exploited to enhance electromagnetic radiation characteristics at optical and near-optical frequencies, particularly within the context of telecommunications engineering.

A comprehensive theoretical and literature background was first established to distinguish the fundamental differences between conventional RF/microwave antennas and plasmonic nanoantennas. It was shown that, unlike RF antennas where metals are commonly approximated as perfect electrical conductors, plasmonic nanoantennas operating at optical frequencies require dispersive material models and careful consideration of surface plasmon polariton (SPP) excitation, field penetration, and ohmic loss mechanisms. These distinctions motivate alternative design and analysis strategies when treating plasmonic structures as radiating elements.

The proposed nanoantenna architecture employs a panda-ring resonator as a resonant photonic circuit capable of supporting whispering gallery modes, which serve as a physically meaningful excitation mechanism for radiation analysis. Using the OptiFDTD simulation platform, the WGM response of the panda-ring resonator was generated and extracted in the time domain. This WGM signal was subsequently transferred to CST Microwave Studio and utilized as a reference excitation source for full-wave electromagnetic simulations. This methodology establishes a consistent and physically realistic framework that bridges photonic resonance analysis and antenna radiation evaluation.

The far-field radiation characteristics of three different configurations—namely a silicon cylinder only, a gold grating only, and the proposed hybrid panda-ring plasmonic nanoantenna—were systematically investigated under identical WGM excitation at the operating frequency of 193.5 THz ($\lambda \approx 1.55 \mu\text{m}$). By applying the same excitation waveform to all configurations, differences in radiation pattern, directivity, and gain could be attributed solely to structural and plasmonic coupling effects rather than excitation inconsistencies.

Simulation results demonstrate that the proposed hybrid panda-ring structure exhibits improved electromagnetic field confinement and enhanced radiation behavior compared to the reference configurations. The integration of the gold grating with the panda-ring resonator facilitates stronger plasmonic coupling and more efficient conversion between localized resonant fields and propagating electromagnetic waves. These findings confirm that the proposed structure can function not only as a photonic resonator but also as an effective plasmonic nanoantenna, suitable for wireless optical and near-optical communication scenarios.

Overall, this research validates the feasibility of using WGM-assisted plasmonic structures as radiating elements in high-frequency communication systems. The proposed design framework and simulation methodology contribute to the ongoing effort to extend classical antenna concepts into the optical regime, supporting the development of compact, high-speed, and integrable communication components.

5.2 Contributions of the Research

The main contributions of this thesis can be summarized as follows:

5.2.1 A panda-ring-based plasmonic nanoantenna architecture integrated with a gold grating is proposed and analyzed for high-frequency communication applications.

5.2.2 A WGM-based excitation methodology is developed, enabling physically consistent radiation analysis by transferring time-domain signals from OptiFDTD to CST Microwave Studio.

5.2.3 The radiation characteristics of plasmonic nanoantennas are evaluated from a telecommunications engineering perspective, emphasizing far-field radiation pattern, directivity, and gain rather than solely near-field enhancement.

5.2.4 A comparative analysis framework is established to fairly assess different plasmonic configurations under identical excitation conditions.

These contributions provide a systematic approach for evaluating plasmonic nanoantennas as radiating elements and support their potential use in future optical and hybrid wireless–optical communication systems.

5.3 Recommendations for Future Work

Although the results obtained in this thesis demonstrate the effectiveness of the proposed plasmonic nanoantenna design, several directions for future research are recommended to further enhance and extend the present work:

5.3.1 Fabrication and experimental characterization of the proposed panda-ring plasmonic nanoantenna would provide valuable validation of the numerical results, particularly with respect to radiation efficiency and coupling behavior.

5.2.2 Future studies may investigate geometrical optimization or active materials to enable tunable resonance and broader operational bandwidth, which are essential for adaptive communication systems.

5.2.3 Incorporating tunable materials such as graphene or phase-change materials could enable dynamic control of radiation characteristics, supporting reconfigurable nanoantenna systems.

5.2.4 Extending the antenna-level analysis to system-level evaluations, such as link budget analysis, modulation schemes, and noise considerations, would further strengthen the applicability of the proposed nanoantenna to practical telecommunication systems.

These contributions provide a systematic approach for evaluating plasmonic nanoantennas as radiating elements and support their potential use in future optical and hybrid wireless-optical communication systems.

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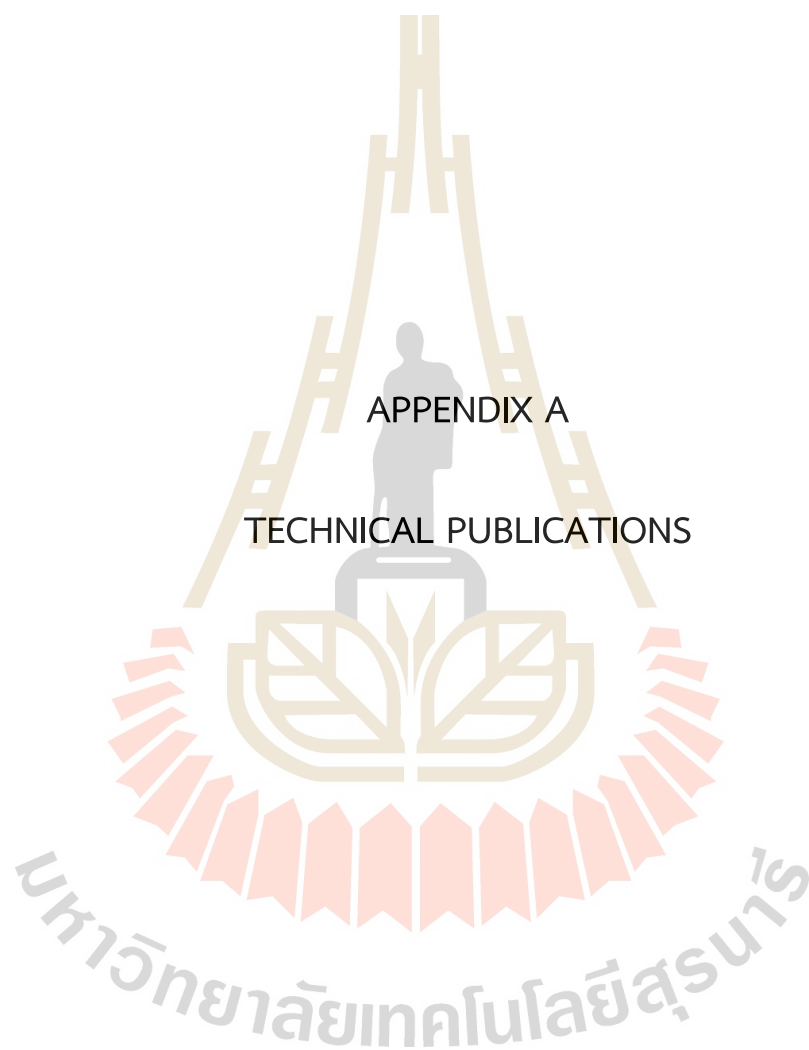
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APPENDIX A

TECHNICAL PUBLICATIONS

LIST OF PUBLICATIONS

International Journal Paper

- Phunklang, S., Jantaupalee, A., Mesawad, P., Yupapin, P., & Krachodnok, P. (2026). **Hybrid Plasmonic-Photonic Panda-Ring Antenna Embedded with a Gold Grating for Dual-Mode Transmission**. *Technologies* 2026, Vol. 14, Page 113, 14(2), 113. doi: 10.3390/technologies14020113
- Arumona, A. E., Punthawanunt, S., Ray, K., Phunklang, S., & Yupapin, P. (2020). **Electron cloud spin generated by microring space-time control circuit for 3D quantum printing**. *Microwave and Optical Technology Letters*, 62(12), 3702–3708. doi: 10.1002/mop.32490

International Conference Paper

- Phunklang, S., Wongsa, F., & Krachodnok, P. (2024). **High-Gain InP-Based Hybrid Plasmonic Nanoantennas Design Using SiO₂-Graphene-Au Stacked Waveguide**. *ICPEI 2024 - Proceedings of the 6th International Conference on Power, Energy and Innovations*, 124–128. doi: 10.1109/ICPEI61831.2024.10749058

Article

Hybrid Plasmonic–Photonic Panda-Ring Antenna Embedded with a Gold Grating for Dual-Mode Transmission

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Abstract

This paper presents a systematic numerical investigation of a hybrid plasmonic–photonic Panda-ring antenna with an embedded gold grating, designed to enable efficient dual-mode radiation for optical and terahertz communication systems. The proposed structure integrates high-Q whispering-gallery mode (WGM) confinement in a multi-ring dielectric resonator with plasmonic out-coupling at the metal–dielectric interface, allowing controlled conversion of resonantly stored photonic energy into free-space radiation. The electromagnetic behavior is analyzed through a hierarchical structural evolution, progressing from a linear silicon waveguide to single-ring, add-drop, and Panda-ring resonator configurations. Gold is modeled using a dispersive Drude formulation with complex permittivity to accurately capture frequency-dependent plasmonic response at 1.55 μm . Power redistribution within the resonator system is described using coupled-mode theory, with coupling and loss parameters evaluated consistently from full-wave numerical simulations. Full-wave simulations using OptiFDTD and CST Studio Suite demonstrate that purely photonic resonators exhibit strong WGM confinement but negligible radiation, while plasmonic gratings alone suffer from low efficiency due to the absence of coherent photonic excitation. In contrast, the proposed hybrid Panda-ring antenna achieves stable and directive far-field radiation under WGM excitation, with a realized gain of approximately 8.05 dBi at 193.5 THz. The performance enhancement originates from synergistic hybrid SPP–WGM coupling, establishing a WGM-driven radiation mechanism suitable for Li-Fi and terahertz wireless applications.

Keywords: hybrid plasmonic–photonic antenna; Panda-ring resonator; surface plasmon polaritons (SPP); whispering-gallery modes (WGMs); dual-mode transmission; Li-Fi communication; terahertz antennas



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1. Introduction

The rapid evolution of wireless and optical communication systems has led to increasing demand for high-frequency, high-efficiency antennas supporting multi-band operation with minimal losses. Millimeter-wave (mmWave) antennas are crucial enablers for fifth-generation (5G) systems due to their high-speed and low-latency connectivity requirements;

however, they also present significant design challenges, including miniaturization and fabrication precision at higher frequencies [1]. Terahertz (THz) frequency bands have been identified as promising candidates for future sixth-generation (6G) communication systems, offering vast bandwidth and ultrahigh data rates, while simultaneously imposing severe challenges related to high propagation loss and compact high-gain antenna realization [2,3]. Next-generation 5G/6G antennas for embedded and Internet-of-Things (IoT) applications further emphasize compact size, reliability, and energy-efficient performance, motivating extensive research into advanced compact and plasmonic antenna architectures [4]. Consequently, emerging design paradigms such as plasmonic antennas are being actively explored for integration into mmWave and THz systems to provide subwavelength confinement, improved gain, and reconfigurable resonance behavior [5].

Plasmonic antennas and related nanostructures have attracted considerable attention due to their ability to manipulate electromagnetic energy at nanometric scales through surface plasmon polaritons (SPPs), enabling enhanced near-field localization and tailored radiation characteristics for high-frequency applications. Several plasmonic heterostructures and nanoantenna configurations have been reviewed for telecommunication purposes, including beam steering, wave guiding, and signal modulation in emerging 6G systems [6]. Plasmonic antennas supporting intense electric or magnetic field hot spots have also been theoretically investigated, highlighting their potential for strong electromagnetic-field control despite intrinsic ohmic losses [7]. To mitigate the limitations of purely plasmonic devices, hybrid plasmonic–photonic waveguide structures have been proposed, combining dielectric waveguide modes with surface plasmon modes to balance field confinement and propagation loss [8]. Furthermore, integration strategies that merge plasmonic elements with dielectric photonic circuits demonstrate how hybrid designs can exploit the advantages of both domains, which is essential for efficient optical communication systems [9].

Among various resonant structures, the Panda-ring resonator [10–16]—a derivative of the microring resonator [17–20]—has attracted significant attention due to its capability to support whispering-gallery modes (WGMs), which enhance optical field confinement and coupling efficiency. WGMs enable high-Q resonances through total internal reflection along curved dielectric interfaces, allowing precise control of resonant wavelengths and power distribution among multiple ports. Integrating plasmonic elements such as metallic gratings into these dielectric resonators further improves light–matter interaction, facilitating hybrid SPP–WGM coupling and enabling additional radiative pathways [21,22]. This hybridization forms the foundation of dual-mode plasmonic operation, where both plasmonic and photonic modes coexist and can be selectively excited depending on system requirements. Dual-mode architectures are particularly advantageous in next-generation communication systems, enabling seamless transitions between wired (fiber-optic) and wireless (Li-Fi or THz) transmission [23]. Compared with conventional microring, disk, and metamaterial resonators, the Panda-ring resonator offers enhanced modal controllability, high-Q whispering-gallery confinement, and precise multi-port power routing [24,25]. Its multi-ring topology provides a versatile platform for hybrid plasmonic–photonic integration, enabling efficient dual-mode operation with improved radiation efficiency and subwavelength field confinement. These characteristics make the Panda-ring resonator particularly suitable for next-generation Li-Fi and terahertz (THz) communication systems [6,26,27]. Building upon these principles, this study proposes a computationally optimized plasmonic Panda-ring antenna embedded with a gold grating, designed to enhance both near-field confinement and far-field radiation characteristics through a hybrid plasmonic–photonic approach. To systematically investigate the evolution of mode confinement and coupling behavior, the proposed design is developed through a hierarchical resonator architecture, starting from a conventional silicon linear waveguide, followed by

silicon ring resonators coupled to single and double linear waveguides. These intermediate configurations provide fundamental insight into power routing, resonance stability, and mode interaction within photonic resonator systems. Based on this progression, the final Panda-ring structure integrates a central microring with two side rings and an embedded gold grating, forming a hybrid antenna capable of supporting strong whispering-gallery mode (WGM) resonance and efficient surface plasmon polariton (SPP) excitation. The overall structural evolution and the final proposed configuration are illustrated in Figure 1.

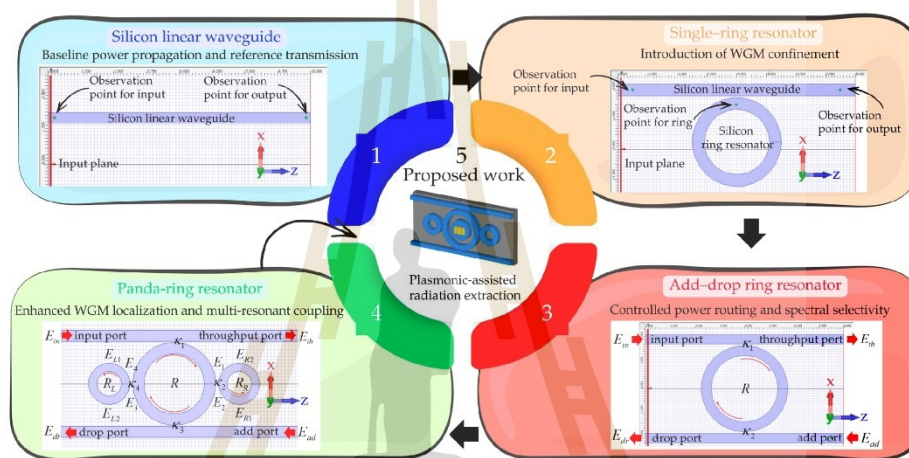


Figure 1. Systematic design evolution of the proposed hybrid plasmonic-photonic Panda-ring antenna. The design starts from a conventional silicon linear waveguide serving as a baseline transmission reference (Structure 1). A single-ring resonator is then introduced to enable whispering-gallery mode (WGM) confinement (Structure 2). An add-drop configuration with double linear waveguides is employed to achieve controlled power routing and spectral selectivity (Structure 3). The Panda-ring resonator further enhances WGM localization and multi-resonant coupling (Structure 4). Finally, the proposed hybrid Panda-ring antenna integrates a plasmonic gold grating to extract radiation from the confined WGM, enabling antenna-like far-field emission (Structure 5).

The embedded gold grating strengthens plasmonic field excitation at the metal-dielectric interface while maintaining high-Q WGM confinement within the silicon waveguide network. This synergy between SPPs and WGMs enables efficient energy redistribution from confined resonant modes toward radiative channels, directional far-field radiation behavior demonstrated in the optical frequency domain, with potential scalability toward terahertz frequencies. In addition, the proposed design addresses key limitations of conventional plasmonic antennas by enhancing electromagnetic field localization and facilitating improved energy coupling, rather than relying solely on purely plasmonic radiation mechanisms. Comprehensive numerical simulations using OptiFDTD 16.0.1 and CST Studio Suite 2025 are performed to analyze the antenna's spectral response, field distribution, gain, and directivity. The simulation results demonstrate that the proposed Panda-ring configuration achieves stable dual-mode transmission with enhanced far-field radiation characteristics, making it well suited for integration into Li-Fi transmitters, future 6G communication modules, and hybrid photonic-plasmonic circuits.

2. Materials and Methods

This section presents the theoretical basis, structural design, and computational approach used to analyze the proposed plasmonic Panda-ring antenna embedded with a gold grating. The study combines analytical modeling and numerical simulations to investigate the antenna's dual-mode plasmonic behavior, governed by the interaction between surface plasmon polaritons (SPPs) and whispering-gallery modes (WGMs).

The gold grating enhances plasmonic confinement at the metal–dielectric interface, while the Panda-ring configuration supports high-Q optical resonance and efficient mode coupling. Full-wave simulations using OptiFDTD and CST Studio Suite are performed to evaluate spectral response, field distribution, and radiation characteristics. The following subsections describe the theoretical foundation, material parameters, and computational setup employed in this work.

2.1. Theoretical Foundation

This section presents the theoretical framework, structural design, and computational methodology used to analyze the proposed plasmonic Panda-ring antenna embedded with a gold grating. The study integrates analytical modeling with full-wave numerical simulations to investigate the dual-mode plasmonic behavior arising from hybrid surface plasmon polariton (SPP) and whispering-gallery mode (WGM) interactions. In the proposed architecture, the embedded gold grating enhances plasmonic field confinement at the metal–dielectric interface, while the Panda-ring resonator supports high-Q optical resonances and efficient mode coupling. Full-wave simulations using Optiwave finite-difference time-domain (FDTD) and CST Studio Suite are conducted to evaluate the spectral response, near-field distribution, and far-field radiation characteristics. The following subsections describe the physical principles, material properties, structural configuration, and computational setup employed in this work.

2.1.1. Surface Plasmon Polaritons (SPPs)

SPPs are electromagnetic waves that propagate along the interface between a metal and a dielectric, resulting from the collective oscillation of free electrons in the metal when excited by incident light. This interaction allows subwavelength field confinement and enhanced near-field coupling [28,29]. The dispersion relation of SPPs is given by the equation:

$$\beta = k_0 \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \quad (1)$$

where β is the propagation constant of the SPP, k_0 is the free-space wavevector, and ϵ_m and ϵ_d represent the complex permittivities of the metal and dielectric, respectively. SPPs exist when the real part of ϵ_m is negative, a condition typically satisfied by noble metals such as gold (Au) and silver (Ag) in the optical and terahertz (THz) frequency ranges. The dielectric function of gold is modeled using the Drude model [30,31], which describes the frequency-dependent behavior of conduction electrons as follows:

$$\epsilon_m(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega^2 + j\omega\gamma} \quad (2)$$

where ϵ_∞ is the high-frequency permittivity, ω_p is the plasma frequency, and γ represents the damping constant associated with electron collisions. This formulation enables accurate modeling of plasmonic resonance within the gold grating structure, which plays a critical role in enhancing field confinement and radiation efficiency.

2.1.2. Whispering-Gallery Modes (WGMs)

WGMs arise when light is confined within a circular dielectric resonator through total internal reflection, forming standing waves that circulate along the perimeter of the resonator. These modes support high quality factors (Q-factors), enabling strong optical confinement and resonance stability [32,33]. The resonance wavelength condition of a WGM is expressed as follows:

$$\lambda_m = \frac{2\pi r n_{eff}}{m} \quad (3)$$

where λ_m is the resonant wavelength, r is the radius of the microring, n_{eff} is the effective refractive index, and m denotes the mode number. In the proposed design, WGMs are excited within the Panda-ring structure composed of a central microring coupled with two side rings. This configuration enhances resonance control and stability, supporting efficient optical energy exchange among the input, throughput, add, and drop ports.

By embedding a gold grating within the central microring, strong hybrid coupling between SPPs and WGMs is achieved [9,23,24]. The metallic grating perturbs the dielectric resonance field, allowing simultaneous excitation of plasmonic and photonic modes, which results in dual-mode transmission. The interaction between these modes improves impedance matching and enhances radiation gain. Moreover, the hybrid coupling minimizes propagation losses by redistributing the electromagnetic field energy between the plasmonic (metallic) and photonic (dielectric) domains [34]. This dual-mode mechanism forms the theoretical basis of the proposed antenna, enabling efficient mode conversion between plasmonic and photonic channels—a key feature for high-performance Li-Fi, 6G, and on-chip optical communication applications [5,9].

2.2. Structural Design of the Proposed Antenna

The proposed plasmonic Panda-ring antenna is designed to achieve strong electromagnetic field confinement and efficient radiation by integrating plasmonic and photonic mechanisms within a compact resonator-based architecture. The structural configuration, illustrated in Figure 2, is based on a Panda-ring resonator circuit composed of a central microring coupled to two side rings and double linear waveguides. This multi-ring topology enhances modal interaction, resonance controllability, and power routing capability, while maintaining compact dimensions suitable for optical and terahertz-frequency operation. As shown in Figure 2a, the structure is implemented on a silicon (Si) waveguide platform supported by a silicon dioxide (SiO₂) substrate. A gold (Au) grating is embedded at the center of the main ring, forming a plasmonic island that enables strong surface plasmon polariton (SPP) excitation at the metal–dielectric interface. The propagation of SPP waves occurs along the metal–dielectric boundary with an evanescent decay in the transverse direction, where the collective oscillation of free electrons in the metal is described by the Drude model. The resulting plasmonic modes exhibit transverse magnetic (TM) polarization and strong field localization, which are essential for efficient near-field enhancement and plasmonic radiation. The Panda-ring resonator supports whispering-gallery modes (WGMs) within the dielectric microring structure, where optical fields circulate along the curved interfaces through total internal reflection.

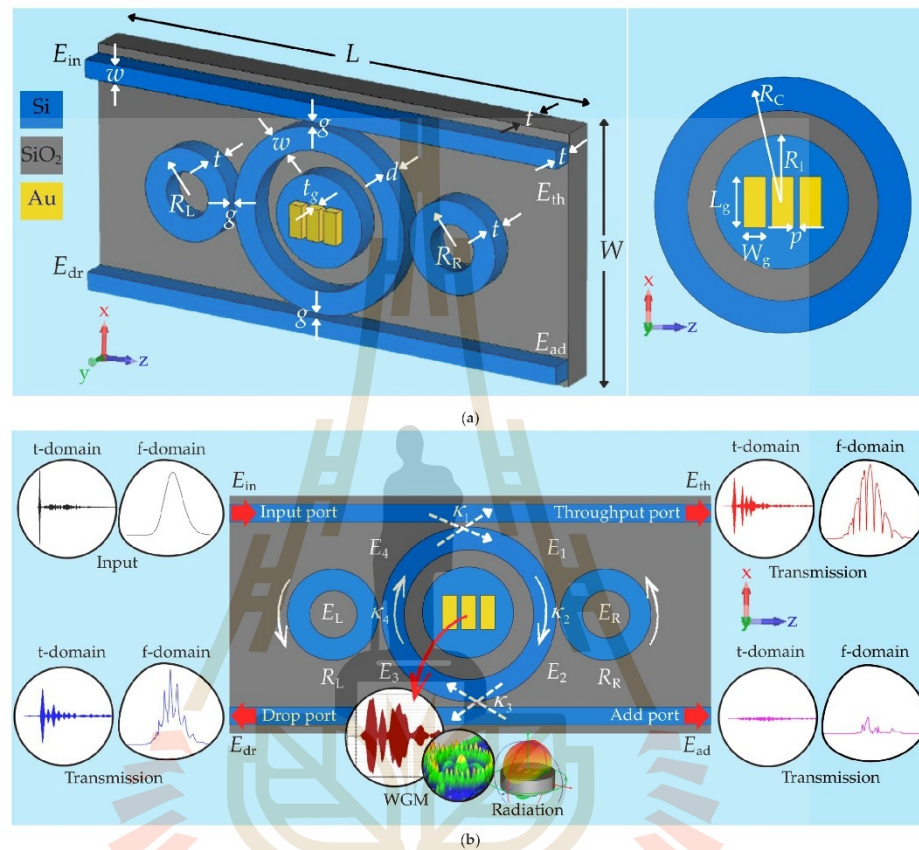


Figure 2. Schematic illustration and operating principle of the proposed hybrid plasmonic-photonic Panda-ring antenna: (a) Three-dimensional structural configuration of the Panda-ring resonator implemented on a silicon (Si) waveguide platform with a silicon dioxide (SiO_2) substrate and an embedded gold (Au) grating at the central ring, including geometric parameters, coupling gaps, and port definitions; (b) Conceptual illustration of whispering-gallery mode (WGM) excitation and signal evolution in both time and frequency domains, showing energy coupling among the input, throughput, drop, and add ports, as well as the WGM-assisted plasmonic radiation mechanism enabled by the embedded Au grating.

In this work, the spectral characteristics associated with plasmonic excitation are identified from the WGM resonance response of the Panda-ring system, enabling effective hybridization between photonic WGMs and plasmonic SPPs. This hybrid SPP–WGM interaction forms the basis of dual-mode operation, where confined photonic energy and localized plasmonic fields coexist and interact coherently within the same structure. As illustrated in Figure 2b, the optical input field E_{in} is injected into the linear silicon waveguide and subsequently coupled into the Panda-ring resonator, where the energy is redistributed among the throughput, drop, and add ports according to the resonant coupling conditions. The throughput port (E_{th}) primarily carries the forward-propagating component of the

input signal and represents the direct transmission path along the bus waveguide. The drop port (E_{dr}) extracts resonantly coupled energy from the Panda-ring structure, exhibiting strong spectral selectivity associated with whispering-gallery mode (WGM) excitation. In contrast, the add port (E_{ad}) is only weakly excited under single-input operation, resulting in a significantly lower output amplitude compared with the throughput and drop ports. This behavior arises from the asymmetric coupling configuration and power redistribution within the Panda-ring resonator, where the add port does not serve as a primary transmission channel in the present excitation scheme. In related photonic systems, this port is often employed as a secondary input to enable dual-input operation or modulation functionality, rather than as a dominant output port. The coupling behavior between the rings and the waveguides is governed by coupling coefficients and attenuation parameters, which determine energy transfer, resonance balance, and phase evolution within the structure. These parameters are obtained from the resonant transmission characteristics of the corresponding waveguide–resonator configurations, ensuring physically consistent energy redistribution among all ports. As a result, the Panda-ring architecture achieves stable resonance behavior, low insertion loss, and strong interaction between neighboring resonators. A summary of the key design parameters and material properties used in the computational modeling is provided in Table 1.

Table 1. Design parameters of the proposed plasmonic Panda-ring antenna.

Symbol	Parameter	Value	Unit
L	Length of silicon linear waveguide, Length of SiO ₂ substrate	10	μm
W	Width of silicon linear waveguide, Width of SiO ₂ substrate	0.3	μm
t	Thickness of silicon linear waveguide, Thickness of SiO ₂ substrate, Thickness of center ring, Thickness of center ring	0.5	μm
R_C	Radius of center ring	1.55	μm
w	Width of center ring, Width of both small rings	0.3	μm
R_L, R_R	Radius of both small rings	0.88	μm
g	Gap size	0.05	μm
-	Silicon refractive index	3.42	-
-	Silicon non-linear refractive index	1.3×10^{-13}	-
-	Gold refractive index	Dispersive Drude model (complex $\varepsilon(\omega)$)	-
t_g	Gold thickness	10	nm
L_g	Gold length	400	nm
W_g	Gold width	200	nm
p	Grating period	300	nm

Based on the structural configuration shown in Figure 2b, the electric-field evolution within the Panda-ring resonator circuit can be described using a coupled-mode analytical model [35]. The field amplitudes at the throughput, drop, and add ports are governed by the coupling coefficients, insertion losses, and phase accumulation along each ring, and can be expressed as follows:

$$E_{th} = \sqrt{1 - \gamma_1} \left(\sqrt{1 - \kappa_1} E_{i1} + j\sqrt{\kappa_1} E_4 e^{-j\frac{\kappa_1 L_P}{4} - jk_n \frac{L_P}{4}} \right) \quad (4)$$

$$E_{dr} = \sqrt{1 - \gamma_3} \left(\sqrt{1 - \kappa_3} E_{i2} + j\sqrt{\kappa_3} E_2 e^{-j\frac{\kappa_3 L_P}{4} - jk_n \frac{L_P}{4}} \right) \quad (5)$$

$$E_{ad} = \sqrt{1 - \gamma_3} \left(\sqrt{1 - \kappa_3} E_d + j\sqrt{\kappa_3} E_2 e^{-j\frac{\kappa_3 L_P}{4} - jk_n \frac{L_P}{4}} \right) \quad (6)$$

where

$$E_1 = \sqrt{1-\gamma_1} \left(\sqrt{1-\kappa_1} E_4 e^{-\frac{\alpha}{2} \frac{L_D}{2} - jk_n \frac{L_D}{2}} + j\sqrt{\kappa_1} E_{i1} e^{-\frac{\alpha}{2} \frac{L_D}{4} - jk_n \frac{L_D}{4}} \right) \quad (7)$$

$$E_2 = \sqrt{1-\gamma_2} \left(\sqrt{1-\kappa_2} E_1 + j\sqrt{\kappa_2} E_{RR} e^{-\frac{\alpha}{2} L_R - jk_n L_R} \right) \quad (8)$$

$$E_3 = \sqrt{1-\gamma_3} \left(\sqrt{1-\kappa_3} E_2 e^{-\frac{\alpha}{2} \frac{L_D}{2} - jk_n \frac{L_D}{2}} + j\sqrt{\kappa_3} E_{i2} e^{-\frac{\alpha}{2} \frac{L_D}{4} - jk_n \frac{L_D}{4}} \right) \quad (9)$$

$$E_4 = \sqrt{1-\gamma_4} \left(\sqrt{1-\kappa_4} E_3 + j\sqrt{\kappa_4} E_{RL} e^{-\frac{\alpha}{2} L_L - jk_n L_L} \right) \quad (10)$$

In these expressions, E_{in} , E_{th} , E_{dr} , and E_{ad} denote the complex electric-field amplitudes at the input, throughput, drop, and add ports, respectively, while E_1 – E_4 represent the circulating field amplitudes at different coupling sections within the Panda-ring resonator. E_{i1} and E_{i2} denote the incident field components at the corresponding coupling junctions, while E_d represents the field component coupled toward the drop port. The terms E_{RR} and E_{RL} correspond to the circulating electric-field amplitudes within the right and left auxiliary rings, respectively. The parameters κ_i and γ_i correspond to the power coupling ratios and insertion-loss factors of the directional couplers, respectively, and α denotes the effective propagation loss coefficient of the waveguide–ring system, accounting for material absorption and radiation-related attenuation. The quantities L_D , L_R , and L_L represent the optical path lengths of the center, right, and left rings, respectively, and $k_n = 2\pi n_{eff}$ is the effective propagation constant of the resonant guided mode supported by the Panda-ring structure.

The coupling and loss parameters employed in the coupled-mode formulation are evaluated consistently with the full-wave resonant responses of the corresponding structures, ensuring agreement between the analytical representation and the numerically observed spectral behavior. These parameters are subsequently used to interpret the power redistribution characteristics discussed in Section 3.2. Under harmonic steady-state conditions, the optical intensity at each port is obtained from the corresponding complex electric-field amplitude extracted from numerical simulations. The optical intensity is proportional to the squared magnitude of the electric field and can be expressed as

$$I = \frac{1}{2} n_{eff} c \epsilon_0 |E|^2 \quad (11)$$

where n_{eff} is the effective refractive index of the guiding medium, ϵ_0 is the vacuum permittivity, c is the speed of light in free space, and E denotes the complex electric-field amplitude at the observation port. This relation is applied consistently to all ports of the resonator structures, including the throughput, drop, and add ports.

2.3. Computational Modeling and Simulation Setup

To comprehensively investigate the dual-mode plasmonic behavior of the proposed Panda-ring antenna embedded with a gold grating, full-wave numerical simulations were conducted using two complementary electromagnetic solvers: Optiwave Finite-Difference Time-Domain (FDTD) and CST Studio Suite. This combined simulation framework enables accurate characterization of near-field photonic–plasmonic interactions in the optical domain, followed by consistent evaluation of far-field radiation behavior under whispering-gallery mode (WGM) excitation.

OptiFDTD was employed to model the optical-domain behavior of the resonator-based structures. To suppress artificial boundary reflections, anisotropic perfectly matched layer (APML) boundary conditions were applied in all spatial directions. The APML consists of 15 absorbing layers with a reflection coefficient of approximately 1.0×10^{-12} , providing effective absorption of both propagating and evanescent plasmonic waves. A uniform

spatial discretization of $\Delta x = \Delta y = \Delta z = 0.045 \mu\text{m}$ was employed to accurately resolve subwavelength field confinement at the metal–dielectric interface. The computational domain comprises $308 \times 55 \times 353$ mesh cells along the X, Y, and Z-axes, respectively. A Gaussian pulse centered at $1.55 \mu\text{m}$ was launched through the silicon linear waveguide. Time-domain electric-field responses were recorded at the throughput, drop, add, and central resonator (island) regions, and subsequently transformed into the spectral domain using discrete Fourier transform (DFT) analysis. To ensure steady-state resonance conditions, the simulation was performed over 20,000 round trips.

This configuration provides reliable evaluation of electric-field distributions and spectral power characteristics, which serve as the basis for extracting the WGM excitation signal used in subsequent radiation analysis. To investigate the antenna radiation characteristics, including gain, and far-field patterns, CST Studio Suite was utilized. Instead of employing an idealized or analytical excitation source, the optical WGM waveform obtained from the OptiFDTD resonator analysis was used as the excitation signal. Specifically, the time-domain WGM response extracted from the Panda-ring resonator (Structure 4) was exported as a CSV file, enabling direct inspection and post-processing using spreadsheet-based tools such as Microsoft Excel [36]. The extracted waveform was then imported into CST Studio Suite as a user-defined excitation via a waveguide port, ensuring physically consistent mode excitation.

The imported WGM signal was defined as a reference excitation signal and subsequently applied to three different island configurations: (i) silicon cylinder only, (ii) gold grating only, and (iii) the proposed hybrid structure, under identical excitation and solver settings. This procedure ensures that any observed differences in far-field radiation characteristics arise solely from structural variations rather than excitation inconsistencies. Far-field radiation patterns were computed at 193.5 THz, corresponding to the dominant resonance frequency identified from the optical-domain analysis. Figure 3 illustrates the complete WGM-based excitation transfer procedure from OptiFDTD to CST Studio Suite. By directly mapping the resonator-generated WGM signal into the antenna simulation environment, the proposed methodology establishes a physically consistent link between near-field photonic resonance and far-field electromagnetic radiation.

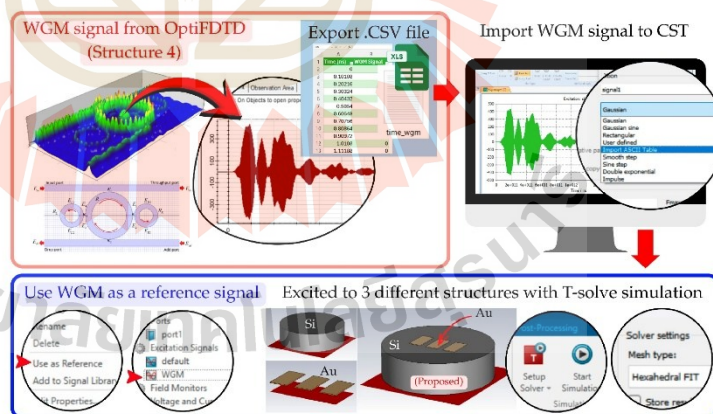


Figure 3. Procedure for WGM-based excitation signal transfer from OptiFDTD to CST Studio Suite: The WGM signal is first extracted from the time-domain response of the Panda-ring resonator

(Structure 4) using OptiFDTD. The extracted WGM waveform is exported as a CSV file and subsequently imported into CST Studio Suite as a user-defined excitation signal. This WGM signal is then used as a common reference excitation to drive three different island configurations—silicon cylinder only, gold grating only, and the proposed hybrid structure—under identical excitation conditions using the time-domain solver. This approach ensures consistent mode excitation and enables a fair comparison of radiation characteristics among different structures.

The combination of OptiFDTD and CST Studio Suite provides a unified computational framework that bridges photonic resonance behavior and antenna radiation analysis. This multi-scale simulation strategy ensures physical consistency between near-field plasmonic–photonic interactions and far-field electromagnetic radiation, thereby enabling reliable assessment of the proposed antenna’s dual-mode transmission capability. The simulation methodology adopted in this work directly supports the electric-field, power intensity, and radiation results discussed in Section 3, confirming the effectiveness of the proposed hybrid plasmonic–photonic Panda-ring antenna design as a proof-of-concept numerical demonstration.

3. Results

This section presents the numerical results of the proposed plasmonic Panda-ring antenna, focusing on the evolution of electromagnetic behavior from resonator-based photonic structures to the hybrid plasmonic–photonic configuration. The analysis includes electric-field distributions, spectral power intensity responses, and far-field radiation characteristics, providing insight into the hybrid SPP–WGM coupling mechanism and its role in enabling dual-mode transmission and enhanced antenna performance.

3.1. Electric-Field Distribution in Resonator-Based Structures

The electric-field distributions of the resonator-based configurations and the proposed structure are summarized in Figure 4 to provide a comparative visualization of field confinement, coupling behavior, and resonant-mode evolution as the structural complexity increases. Unlike the linear waveguide baseline, which primarily supports forward-guided propagation with limited field localization, the resonator-based structures exhibit pronounced field enhancement arising from resonant circulation and evanescent coupling mechanisms. This progressive evolution of the field distribution establishes the physical foundation for the hybrid plasmonic–photonic response and dual-mode operation of the proposed antenna. For Structure 1, which consists of a simple silicon linear waveguide, no detailed electric-field distribution analysis is presented. In general, propagation loss in a straight waveguide accumulates with transmission length due to material absorption and scattering effects. However, in this work the waveguide length is intentionally designed to be extremely short, on the order of a few micrometers, resulting in negligible attenuation over the propagation distance considered. Consequently, the linear waveguide primarily serves as a reference for guided-wave transmission rather than a resonant structure. The subsequent analysis therefore focuses on resonator-based configurations (Structures 2–5), where field localization, resonant buildup, and coupling-induced redistribution dominate the electromagnetic behavior and are directly relevant to the dual-mode operation of the proposed antenna.

For the silicon ring resonator coupled to a single linear waveguide (Structure 2), the electric-field distribution demonstrates a clear buildup of circulating fields along the ring perimeter, indicating the excitation of whispering-gallery-like resonant modes. Strong field localization is observed near the coupling region between the straight waveguide and the ring, confirming efficient evanescent coupling and power transfer from the bus waveguide into the resonator cavity. Outside the coupling zone, the field intensity decays

rapidly, highlighting effective spatial confinement within the resonator. This configuration represents the fundamental resonant behavior, where energy is primarily stored and circulated within a single ring, providing a baseline for subsequent multi-resonator coupling analysis. When the resonator topology is extended to include a double linear waveguide configuration (Structure 3), the electric-field distribution reveals a more complex coupling pattern. In addition to the circulating field within the ring, enhanced field intensity appears along both bus waveguides, indicating bidirectional energy exchange through multiple coupling interfaces. The presence of two waveguides introduces additional coupling paths, leading to increased field redistribution and partial symmetry breaking in the spatial field profile. This configuration enables more flexible power routing between input, through-put, drop, and add ports, while maintaining strong resonant confinement inside the ring, consistent with the multi-port coupling scheme illustrated in Figure 2b. The resulting field pattern illustrates how multi-port access can be achieved without significantly degrading resonance stability, an essential feature for integrated photonic circuits and antenna feeding networks. Further enhancement of resonant interaction is observed in the Panda-ring resonator configuration without plasmonic loading (Structure 4), where a central ring is coupled to two side rings. The electric-field distribution shows strong field localization not only within the main ring but also in the adjacent side rings, indicating efficient inter-ring coupling and collective mode formation. The coupled-ring topology promotes energy exchange among the resonators, leading to extended field circulation paths and increased effective interaction length. As a result, higher field intensity and improved confinement are achieved compared with single-ring configurations, indicating its suitability as a high-Q WGM excitation and energy-feeding platform. The presence of multiple resonant pathways also facilitates mode splitting and stabilization, which is advantageous for achieving controlled resonance behavior and enhanced spectral selectivity.

The most significant modification of the electric-field distribution occurs in the proposed hybrid plasmonic-photonic Panda-ring structure embedded with a gold grating (Structure 5). As shown in Figure 4, the field intensity is strongly enhanced at the central ring region where the metallic grating is embedded, while high-intensity circulating fields are preserved along the dielectric ring perimeter. This behavior indicates the simultaneous excitation of whispering-gallery modes within the dielectric resonator and surface plasmon polaritons at the metal-dielectric interface. The strong spatial overlap between the evanescent plasmonic field supported by the gold grating and the circulating WGM field confined in the silicon ring confirms the formation of hybrid SPP-WGM coupling. The hybrid coupling mechanism significantly alters the field distribution by redistributing electromagnetic energy between plasmonic and photonic domains. While the dielectric resonator maintains high-Q confinement and stable circulation, the metallic grating introduces localized plasmonic hotspots that enhance near-field intensity and facilitate controlled radiative leakage. Figure 4c,d are plotted using the same color scale to enable direct visual comparison. Although the color bars are identical, the WGM field intensity at the center of the ring in Figure 4d is clearly higher than that in Figure 4c. This enhancement arises from the presence of the plasmonic gold grating, which strengthens local field confinement through plasmonic-photonic coupling, rather than from any difference in color normalization.

This dual behavior enables efficient conversion between guided photonic modes and radiative plasmonic modes, thereby supporting dual-mode transmission. The resulting field pattern exhibits both strong near-field localization, characteristic of plasmonic excitation, and extended circulating fields associated with photonic resonance, providing a physical basis for the observed improvements in radiation efficiency and gain. Comparing the field distributions across all resonator-based structures highlights the critical role of structural evolution in enabling dual-mode operation. Single-ring and multi-bus configurations pri-

marily enhance photonic resonance and power routing, whereas the Panda-ring topology introduces cooperative resonant coupling that strengthens field confinement. The integration of the gold grating further extends this capability by activating plasmonic modes that interact constructively with WGMs. This synergy enhances impedance matching, reduces propagation loss through energy redistribution, and improves far-field radiation characteristics without sacrificing resonance stability.

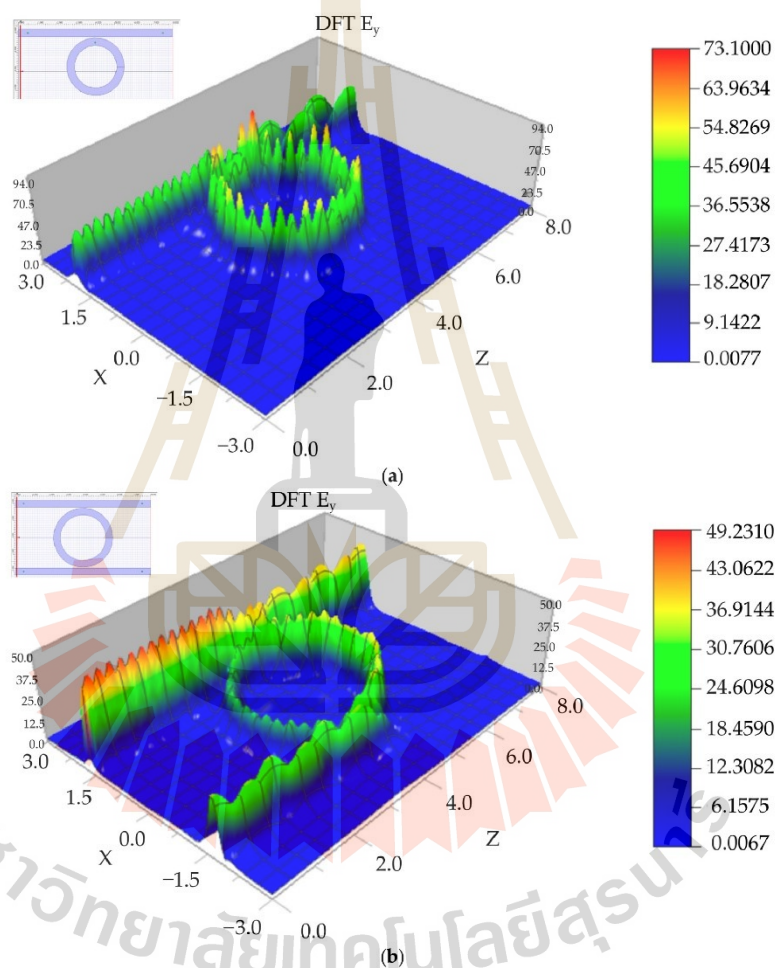


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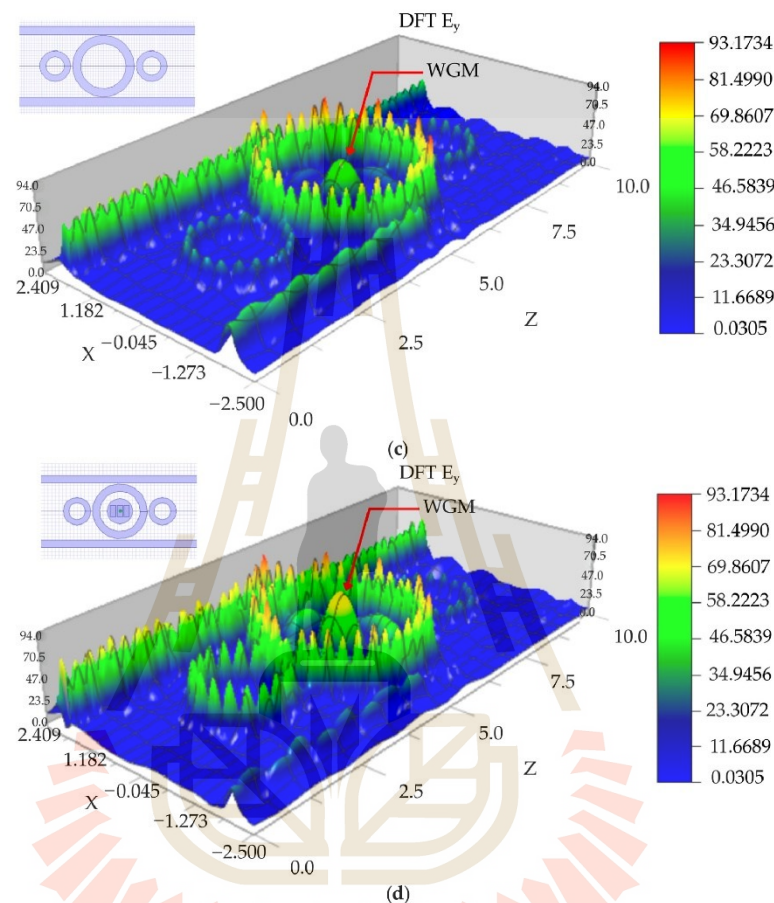


Figure 4. Simulated electric-field (E-field) distributions of resonator-based structures showing the transition from photonic whispering-gallery modes to hybrid plasmonic–photonic field confinement: (a) single-waveguide ring resonator; (b) double-waveguide ring resonator; (c) Panda-ring resonator; and (d) hybrid plasmonic Panda-ring antenna with embedded gold grating.

3.2. Spectral Power Intensity Analysis of Resonator-Based Structures

Figure 5 presents the simulated power intensity spectra of the resonator-based configurations, illustrating the evolution of spectral characteristics from purely photonic resonators to the proposed hybrid plasmonic Panda-ring antenna. The results provide insight into wavelength-dependent power redistribution, resonant-mode formation, and the transition toward dual-mode operation governed by hybrid surface plasmon polariton (SPP) and whispering-gallery mode (WGM) coupling mechanisms. For Structure 2, which consists of a silicon ring resonator coupled to a single linear waveguide, the power intensity response is dominated by fundamental WGM resonances. As shown in Figure 5a, the throughput port exhibits attenuation notches at resonance wavelengths, corresponding to efficient coupling of optical energy into the ring cavity. The complementary behavior observed at

the drop port in Figure 5b confirms selective wavelength extraction characteristic of add-drop filter operation. In this configuration, energy redistribution is primarily controlled by photonic resonance, with limited modal interaction and negligible add-port excitation, consistent with conventional add-drop resonator behavior dominated by single-ring WGM confinement.

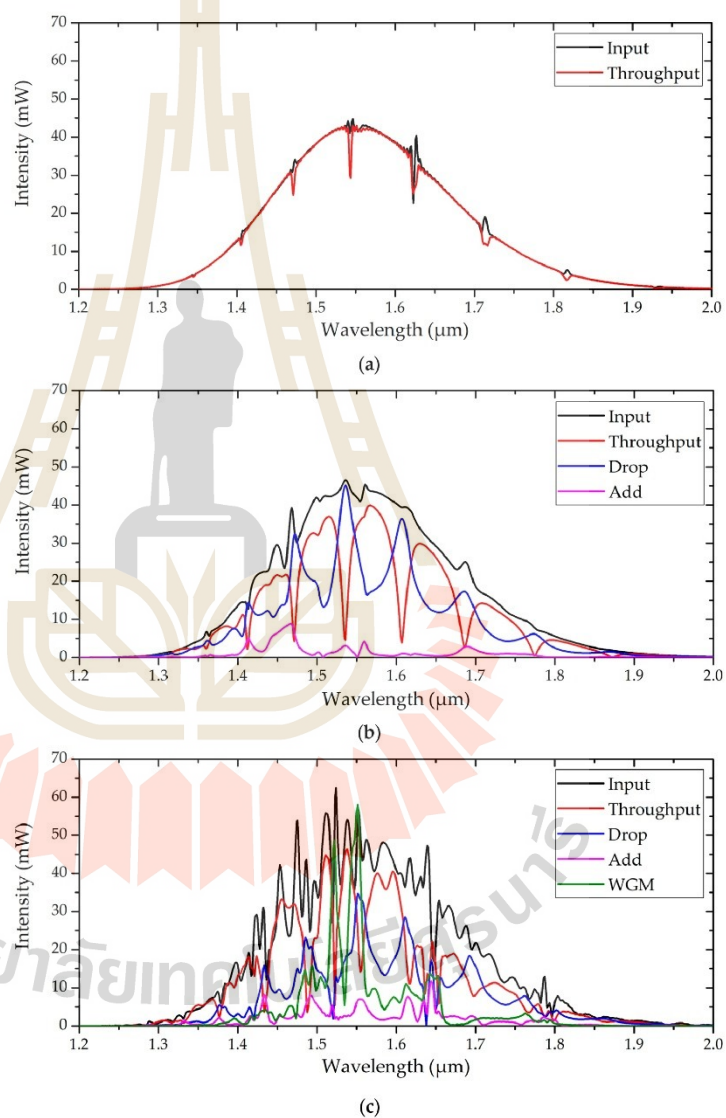


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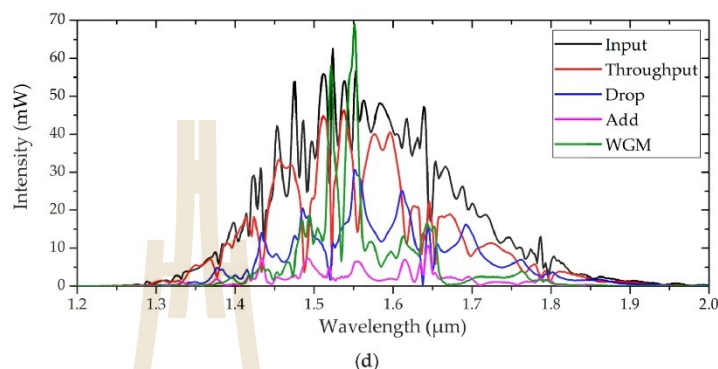


Figure 5. Power intensity spectra of the resonator-based configurations: (a) silicon ring resonator with a single linear waveguide (Structure 2); (b) silicon ring resonator with double linear waveguides (Structure 3); (c) Panda-ring resonator (Structure 4); and (d) hybrid plasmonic Panda-ring antenna embedded with a gold grating (Structure 5).

The introduction of a second linear waveguide in Structure 3 significantly modifies the spectral response. As illustrated in Figure 5b, the throughput, drop, and add ports simultaneously exhibit pronounced resonance features. The presence of dual bus waveguides enables bidirectional coupling and increases the number of accessible coupling paths, resulting in enhanced power routing flexibility, consistent with the multi-port coupling scheme illustrated in Figure 2b. Compared with the single-waveguide configuration, Structure 3 demonstrates increased resonance density and stronger port-to-port interaction, indicating improved controllability of photonic power flow while maintaining stable WGM confinement. Figure 5c shows the power intensity spectra of Structure 4, employing a Panda-ring resonator composed of a central microring coupled to two auxiliary side rings. The multi-ring topology introduces coherent inter-ring coupling, leading to mode splitting and resonance broadening across the wavelength spectrum. Strong WGM intensity peaks are observed, accompanied by deeper attenuation at the throughput port and enhanced extraction at the drop port. The add port also exhibits noticeable modulation, reflecting bidirectional energy exchange enabled by the coupled resonator system. These results confirm that the Panda-ring architecture significantly enhances modal interaction and resonance controllability compared with conventional single-ring configurations, serving as a critical intermediate step toward hybrid plasmonic integration, particularly as a stable high-Q WGM excitation platform. The spectral response of the proposed Structure 5, shown in Figure 5d, reveals a pronounced enhancement in power intensity characteristics due to the incorporation of a gold grating within the Panda-ring resonator. Sharp and high-amplitude WGM peaks appear near the central resonance wavelengths, indicating strong electromagnetic field localization induced by efficient SPP excitation at the metal-dielectric interface. Compared with the purely photonic Panda-ring, the hybrid structure exhibits deeper throughput attenuation, stronger drop-port extraction, and increased add-port modulation, demonstrating effective hybridization between plasmonic and photonic modes.

The coexistence of enhanced WGM resonances and redistributed port intensities confirms the emergence of dual-mode operation in Structure 5. In this regime, photonic WGMs provide resonance stability and efficient power routing, while plasmonic SPPs contribute subwavelength field confinement and localized field enhancement. The hybrid

SPP–WGM interaction improves impedance matching and energy transfer efficiency, resulting in superior spectral selectivity and power redistribution compared with all preceding photonic configurations.

3.3. Far-Field Radiation and Gain Characteristics Under WGM Excitation

The far-field radiation performance of the proposed antenna is evaluated under whispering-gallery mode (WGM) excitation at an operating frequency of 193.5 THz (corresponding to a wavelength of approximately 1.55 μm). To ensure a fair and physically consistent comparison, the same WGM waveform extracted from the Panda-ring resonator is applied as the excitation source for all investigated island configurations. Three cases are considered: a silicon cylinder only, a gold grating only, and the proposed hybrid Panda-ring antenna. For the silicon-cylinder-only configuration shown in Figure 6a, the realized gain reaches 4.12 dBi, while the radiation efficiency and total efficiency are -0.3786 dB and -3.101 dB, respectively. These results indicate that although the dielectric resonator supports strong WGM confinement with relatively low material loss, a large fraction of the electromagnetic energy remains stored within the high-Q resonator, resulting in limited conversion into free-space radiation and consequently moderate gain.

When the gold-grating-only configuration is considered, as illustrated in Figure 6b, the realized gain decreases to -0.539 dBi, accompanied by a radiation efficiency of -6.764 dB and a total efficiency of -7.826 dB. This configuration is structurally analogous to the plasmonic antenna reported in Ref. [10], where a similar grating-based radiating element was investigated; the reported radiated power was approximately 0.9 mW, corresponding to about -0.5 dB on a logarithmic scale, which shows good quantitative agreement with the gain level obtained in this work. Minor discrepancies can be attributed to differences in the material platform and surrounding dielectric environment, which affect plasmonic confinement, ohmic loss, and impedance matching. Despite these differences, both studies exhibit a cardioid-like radiation pattern in the magnetic field (H-plane), indicating a common plasmonic radiation mechanism governed by asymmetric surface current distribution along the grating. Nevertheless, in the absence of a coherent photonic energy-feeding mechanism, plasmonic fields remain weakly organized and strongly affected by ohmic dissipation, resulting in limited radiation efficiency and degraded overall performance.

In contrast, the proposed hybrid Panda-ring antenna shown in Figure 6c exhibits a pronounced enhancement in far-field radiation characteristics. The realized gain increases to 8.05 dBi, while the radiation efficiency and total efficiency improve to -1.20 dB and -2.20 dB, respectively. The radiation pattern is dominated by a stable broadside main lobe with improved angular symmetry and controlled sidelobe levels, indicating efficient and directive energy extraction from the resonator into free space. Compared with the silicon-only configuration, the hybrid structure achieves an approximate gain enhancement of 3.9 dB and a total-efficiency improvement of nearly 0.9 dB. Relative to the gold-grating-only case, the gain enhancement exceeds 8.5 dB, accompanied by a total-efficiency improvement of more than 5.6 dB. These results demonstrate that neither dielectric WGM confinement nor plasmonic radiation alone is sufficient to achieve high-performance radiation under WGM excitation. Similar gain enhancement trends have been reported in hybrid plasmonic nanoantenna systems [3], where the introduction of gold-based plasmonic elements resulted in measurable gain improvement due to enhanced radiation efficiency and effective mode conversion.

The electric-field distributions in Figure 7 provide direct physical insight into these far-field behaviors. Under identical WGM excitation, the silicon-only configuration (Figure 7a) exhibits strong field confinement along the resonator boundary with minimal leakage into free space, explaining its moderate gain and limited total efficiency. For the gold-grating-

only case (Figure 7b), localized plasmonic excitation is observed around the metallic elements; however, the field distribution lacks global coherence and is strongly affected by ohmic loss, consistent with the poor radiation efficiency obtained in the far-field analysis.

By contrast, the proposed hybrid Panda-ring antenna (Figure 7c) exhibits spatially coherent electric-field localization simultaneously within the dielectric resonator and at the metal–dielectric interface of the embedded gold grating. This redistribution reflects efficient overlap between whispering-gallery modes and surface plasmon polaritons, enabling momentum matching and controlled radiative out-coupling. As a result, resonantly stored energy is efficiently extracted into free space without compromising resonance stability. These observations confirm that the enhanced gain and efficiency originate from the synergistic WGM-assisted plasmonic radiation mechanism, establishing the proposed Panda-ring antenna as a promising platform for Li-Fi transmitters, terahertz wireless links, and integrated photonic–plasmonic communication systems.

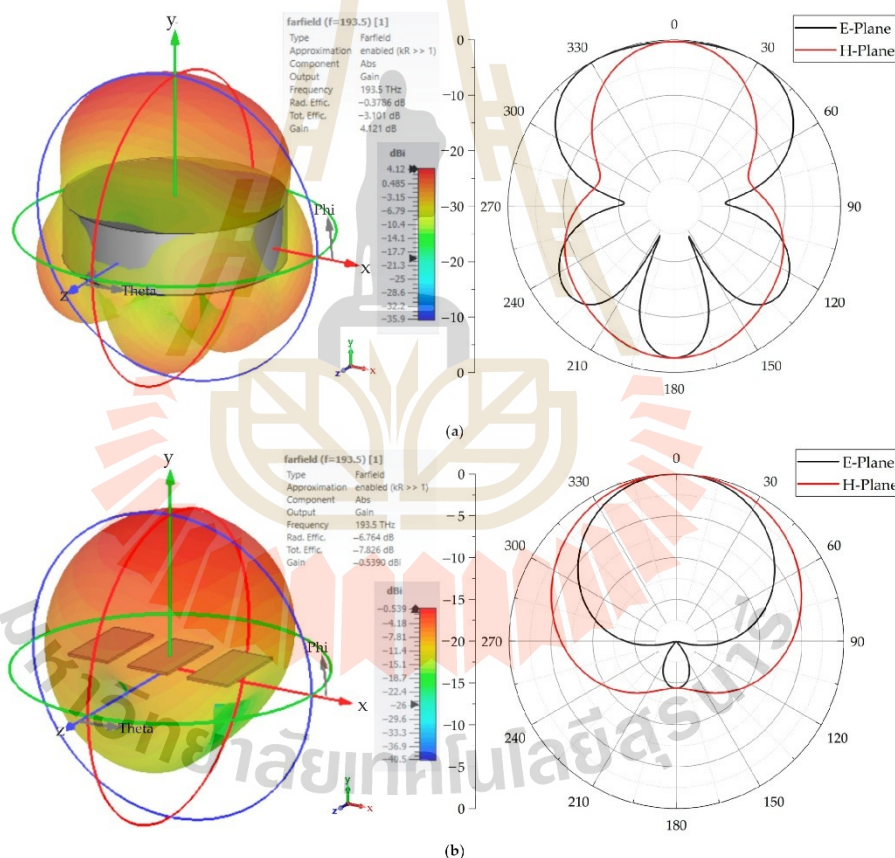


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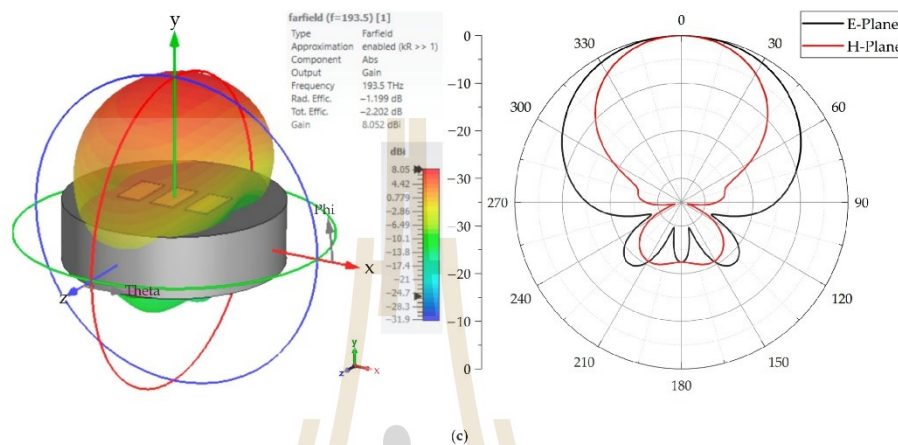


Figure 6. Far-field radiation characteristics under identical WGM-driven excitation at 193.5 THz for three different island configurations: (a) silicon cylinder only; (b) gold grating only; (c) the proposed hybrid Panda-ring antenna with embedded gold grating.

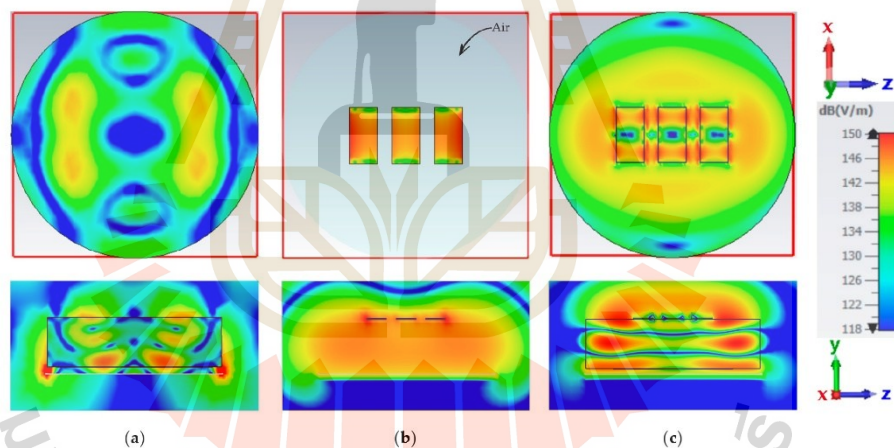


Figure 7. Electric-field distribution at 193.5 THz under identical WGM excitation for (a) silicon cylinder only, (b) gold grating only, and (c) the proposed hybrid Panda-ring antenna. The hybrid structure exhibits significantly enhanced field localization and coherent plasmonic-photonic coupling compared with the individual components.

4. Discussion

This section discusses the physical implications and performance trends derived from the comparative investigation of the five studied structures summarized in Table 2. Rather than reiterating numerical results, the discussion focuses on the evolution of dominant electromagnetic mechanisms, governing the transition from purely photonic energy confinement to efficient whispering-gallery mode (WGM)-driven radiation in the proposed hybrid plasmonic-photonic Panda-ring antenna. Particular emphasis is placed on how incremen-

tal structural evolution modifies field localization, spectral controllability, and radiation efficiency, ultimately enabling stable dual-mode transmission suitable for high-frequency Li-Fi and terahertz (THz) applications.

Table 2. Comparative analysis of the investigated structures and their application relevance.

Configuration Description	Dominant Physical Mechanism	Field Confinement, Spectral Behavior	Radiation Capability	Application Relevance	Ref.
Linear waveguide	Guided-wave propagation (Linear photonic)	Weak confinement; no resonance	No effective radiation	Optical interconnect baseline, reference structure	[37–39]
Ring resonator with single bus waveguide	WGM (Linear resonator)	Basic WGM confinement; limited spectral control	Very weak radiation (trapped energy)	Optical filtering, sensing	[33,37,40–42]
Ring resonator with dual bus waveguides (add-drop)	WGM with port coupling (Linear resonator)	Improved power routing; defined through/drop response	Weak radiation leakage	Resonator-based modulation, sensing, photonic routing	[17–20,43]
Panda-ring resonator (three coupled rings)	Coupled WGM (Linear high-Q resonators)	Strong confinement; excellent modal controllability	Indirect radiation; suitable as feeder	WGM-based excitation source, optical signal processing	[10–16,35]
Panda-ring with embedded Au/Ag grating (Proposed)	Hybrid SPP-WGM coupling (Hybrid plasmonic-photonic)	Subwavelength confinement; dual-mode behavior	Enhanced field localization/energy redistribution	Li-Fi transmitters, THz antennas, photonic-plasmonic transceivers	[10,11,44]

4.1. Evolution from Linear Photonic Guiding to Resonator-Based Confinement

The linear silicon waveguide (Structure 1) serves as a fundamental reference, supporting guided-wave propagation without resonant enhancement. Owing to the absence of feedback and modal confinement mechanisms, electromagnetic energy remains weakly localized and does not contribute to radiation. While such waveguides are indispensable as optical interconnects and excitation channels in integrated photonic systems, their functionality is inherently limited to signal transport rather than energy storage or radiation [37–39]. Accordingly, Structure 1 is treated solely as a transmission baseline and excluded from detailed radiation analysis. Introducing a ring resonator with a single bus waveguide (Structure 2) enables whispering-gallery mode (WGM) formation through total internal reflection along the curved dielectric interface [32,37,40]. This configuration significantly enhances optical field confinement compared with linear waveguides; however, the energy remains largely trapped within the resonator due to its high-Q nature and minimal radiation leakage. Consequently, Structure 2 is well suited for optical filtering and refractive-index sensing but remains ineffective as a radiating element [33,41,42].

The dual-bus (add-drop) ring resonator (Structure 3) extends this concept by providing controlled power routing through distinct throughput and drop ports [33]. Although spectral selectivity and functional versatility improve, the dominant physical mechanism remains linear WGM confinement, and radiation leakage remains weak, unintentional, and poorly directed, indicating that conventional add-drop resonators are not inherently compatible with efficient antenna operation [17–20,43]. These observations are consistent with the spectral redistribution results presented in Section 3.2, confirm that port engineering alone is insufficient to enable efficient antenna radiation.

4.2. Panda-Ring Resonator as a High-Q WGM Excitation Platform

The Panda-ring resonator (Structure 4), composed of a central ring coupled with two auxiliary side rings, represents a significant advancement in modal controllability and resonance stability. The multi-ring topology supports strongly coupled WGMs with enhanced

quality factors, enabling precise control over resonance conditions and power distribution among multiple coupling paths [10–12,14–16]. Despite its improved modal richness and higher stored electromagnetic energy, Structure 4 remains predominantly non-radiative, as demonstrated by its limited far-field response under WGM excitation. Importantly, this behavior highlights a critical distinction: the Panda-ring resonator functions most effectively as a high-Q WGM excitation and energy-feeding platform rather than as a direct radiating element [13,15,35]. The ability of Structure 4 to generate stable, coherent WGM waveforms forms a crucial bridge between photonic resonators and antenna systems, enabling controlled excitation of downstream radiating structures without compromising resonance stability.

4.3. Hybrid SPP–WGM Coupling and Dual-Mode Radiation Mechanism

The proposed structure (Structure 5) introduces a fundamental shift in physical behavior by embedding a gold (Au) grating into the Panda-ring resonator. This modification facilitates strong coupling between WGMs and surface plasmon polaritons (SPPs) at the metal–dielectric interface [28–30], resulting in a hybrid plasmonic–photonic system. Unlike purely photonic resonators, this hybrid configuration enables subwavelength field confinement and momentum matching, allowing confined energy to couple into free-space radiation modes [22,23]. The electric-field and power intensity distributions demonstrate pronounced localization at the Au grating region, confirming the excitation of plasmonic modes. Importantly, comparative analysis with silicon-only and gold-grating-only configurations confirms that plasmonic excitation alone lacks sufficient coherence and radiation efficiency in the absence of photonic energy feeding. When driven by WGM-based excitation from Structure 4, the proposed antenna exhibits stable and directional far-field radiation with enhanced gain across multiple optical and THz frequencies. This behavior validates the proposed dual-mode transmission mechanism, where photonic WGMs provide high-Q energy storage and plasmonic SPPs act as an efficient radiation channel [10,11,24]. From a broader perspective, the present results extend the hybrid plasmonic antenna concept introduced in Ref. [3] by demonstrating that plasmon-assisted gain enhancement can be effectively driven by high-Q whispering-gallery mode excitation rather than direct plasmonic feeding.

Unlike Ref. [10], which effectively corresponds to the gold-grating-only configuration relying on localized plasmonic excitation, the present work demonstrates that such a structure alone is insufficient to achieve efficient and directive radiation. By introducing WGM-assisted photonic energy feeding through the Panda-ring resonator, the proposed hybrid architecture establishes a distinct radiation mechanism based on coherent plasmonic–photonic coupling. The observed conversion of WGM-confined energy into directional radiation can be interpreted through plasmon-mediated emission dynamics, analogous to propagating surface-plasmon-induced photon emission processes previously reported in quantum emitter–plasmon systems [45]. Compared with conventional plasmonic antennas, which often suffer from excessive ohmic losses and poor impedance matching [6,7], the proposed hybrid architecture balances confinement and radiation efficiency through coordinated photonic–plasmonic interaction, results in superior performance relative to both purely photonic and purely plasmonic designs [8,9,25,26].

From an application perspective, the comparative analysis clearly illustrates that only the proposed hybrid Panda-ring antenna achieves the necessary combination of field confinement, spectral controllability, and radiation capability required for next-generation communication systems. Structures 1–3 are limited to guided-wave or resonator-based photonic applications, while Structure 4 functions optimally as a non-radiative WGM excitation platform. In contrast, Structure 5 enables direct conversion of confined optical

energy into directional electromagnetic radiation. These characteristics make the proposed antenna particularly attractive for Li-Fi transmitters, THz wireless links, and photonic-plasmonic transceivers, where seamless integration between optical signal processing and wireless radiation is required. Furthermore, the computational design framework adopted in this work allows scalable optimization across frequency bands, supporting future extensions toward tunable or reconfigurable hybrid antenna systems.

From an application perspective, the comparative analysis clearly illustrates that only the proposed hybrid Panda-ring antenna simultaneously achieves strong field confinement, spectral controllability, and efficient radiation, which are essential for next-generation communication systems. Structures 1–3 remain limited to guided-wave or resonator-based photonic applications, while Structure 4 functions optimally as a non-radiative WGM excitation platform. In contrast, Structure 5 enables direct conversion of confined optical energy into directional electromagnetic radiation, making it particularly attractive for Li-Fi transmitters, THz wireless links, and photonic-plasmonic transceivers. From a practical standpoint, the proposed hybrid plasmonic-photonic Panda-ring antenna should be regarded as a proof-of-concept platform for demonstrating WGM-driven radiation extraction. While the numerical results confirm the feasibility of optical-domain radiation, challenges related to fabrication tolerance, metallic ohmic loss, and efficient out-coupling remain. The coupling gap, intentionally designed to enhance plasmonic-photonic interaction, is expected to be sensitive to fabrication variations. Qualitatively, increasing the gap weakens coupling and radiation leakage, whereas reducing it enhances coupling at the expense of increased loss. Although a detailed tolerance analysis is beyond the scope of this work, the present results establish a clear operating principle and provide a reference for future tolerance-aware optimization and experimental validation.

5. Conclusions

This work has presented a systematic numerical investigation of a hybrid plasmonic-photonic Panda-ring antenna incorporating an embedded gold grating, with the aim of enabling efficient dual-mode radiation for high-frequency optical and terahertz communication systems. By progressively evolving the structure from a linear silicon waveguide to increasingly complex resonator-based configurations, the study has clarified the respective roles of photonic confinement, resonant coupling, and plasmonic radiation in determining antenna performance. The results confirm that conventional photonic structures, including single-ring and add-drop microring resonators, primarily support whispering-gallery mode (WGM) confinement with negligible radiation, making them unsuitable for antenna applications despite their effectiveness in filtering and sensing. The Panda-ring resonator composed of three coupled rings significantly enhances modal controllability and resonance stability, but remains predominantly non-radiative, functioning instead as an efficient high-Q WGM excitation and energy storage platform.

A fundamental transition in electromagnetic behavior is achieved by embedding a metallic gold grating into the Panda-ring resonator, thereby activating strong hybrid coupling between WGMs and surface plasmon polaritons (SPPs) at the metal-dielectric interface. This hybrid SPP-WGM interaction enables subwavelength field localization while simultaneously facilitating efficient momentum matching and controlled radiative leakage. Comparative analyses demonstrate that plasmonic structures alone are insufficient to produce efficient and directive radiation in the absence of coherent photonic energy feeding. In contrast, the proposed hybrid architecture exploits WGM-assisted excitation to convert confined photonic energy into stable and directional free-space radiation, establishing a physically distinct dual-mode radiation mechanism. Full-wave simulations performed using OptiFDTD and CST Studio Suite demonstrate that the proposed hybrid Panda-ring

antenna achieves stable far-field radiation with a realized gain of approximately 8.05 dBi at the dominant resonant optical frequency of 1.55 μm (≈ 193.5 THz), while maintaining acceptable radiation and total efficiencies despite intrinsic plasmonic losses. The observed radiation behavior is attributed to plasmon-mediated emission dynamics enabled by the embedded gold grating, which functions as a controlled out-coupling interface rather than a passive scattering element. In contrast to previously reported gold-grating-only configurations, such as Ref. [10], the present design establishes a WGM-driven radiation mechanism based on coherent plasmonic–photonic coupling, leading to substantially improved radiation coherence, gain, and overall efficiency.

Overall, the results demonstrate that the hybrid plasmonic–photonic Panda-ring antenna effectively combines the advantages of high-Q photonic resonators and plasmonic radiators, overcoming key limitations associated with each individual domain. The proposed structure provides a compact and versatile platform for seamless optical-to-wireless energy conversion, making it promising for future Li-Fi transmitters, terahertz wireless links, and integrated photonic–plasmonic transceivers. It should be emphasized that the present study represents a proof-of-concept demonstration based on numerical analysis; further investigations addressing fabrication tolerances, material dispersion and loss modeling, and experimental validation will be required to advance the design toward practical implementation.

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RESEARCH ARTICLE

Electron cloud spin generated by microring space-time control circuit for 3D quantum printing

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Abstract

A three-dimensional (3D) quantum printing technique is proposed that uses electron spin cloud projections generated by microring-embedded gold grating. A dark soliton pulse with a center wavelength of 1.50 μm excites the gold grating, leading to electron cloud oscillations. By using suitable parameters, the whispering gallery mode is obtained, which is the result of trapping light (electrons) inside the silicon microring. The plasma wave frequency is generated at the Bragg wavelength at which the electron density is obtained. The electron spin-down and spin-up forms the x-axis and y-axis along the propagation z-axis. In this proposal, the propagation wave axis is applied to increase the printing resolution. The printing points are formed by the spin-down, spin-up, and no spin associated with $[x, y, z]$ as $[1, 0, -]$. The electron spins are distinguished by the time sequence and by modulating with the Gaussian pulse of 1.30, 1.10, and 0.80 μm ,

from which the spin states of the electron can be detected and characterized. The shortest space-time paradox gap is around 50 fs, which is the limitation of all measurements (observations). The electron transport spin projection is achieved with respect to the time function in which the 3D image is printed with a resolution of 50 fs (10^{-15} s). In application, the trapped electron densities within the circuit are made possible via wireless connection for long-distance transmission.

KEYWORDS

electron cloud transport, electron spin, quantum printing, microring circuit

1 | INTRODUCTION

Three-dimensional printing (3D) is also called additive manufacturing and involves creating 3D solid objects from a digital file. This starts with the fabrication of 3D objects layer by layer directly from computer-aided design (CAD) drawings. It can be used to create complex shapes or designs of objects by using 3D modeling software. The objects' fabricated layers are printed using a 3D printer,¹ and the first thing needed for 3D printing is 3D modeling software. The working principle of a 3D printer is similar to that of an inkjet printer, where the 3D models are built layer upon layer from the bottom upward by printing over the same area repeatedly. The printer builds the 3D model directly from the 3D CAD drawing using many two-dimensional (2D) prints that sit on top of one another without paper in between. The printer does not apply ink to the deposit of the molten plastic layer, whereas the 2D prints that sit on top of one another are joined together to create the 3D object. There are different methods used for 3D printing, including vat photopolymerization, material jetting, binder jetting, material extrusion, powder bed fusion, sheet lamination, and directed energy deposition. A 3D printer that uses vat photopolymerization and material jetting methods makes use of ultraviolet light in the hardening or fabrication of 3D structural objects.² Other techniques have been employed by different researchers in printing 3D color objects.^{3–8} For example, Yejing et al⁹ used photonic crystals and heat-shrinking techniques in the printing of 3D structural color objects at a microscopic scale. Jingfang et al¹⁰ developed a bis furan cyclohexane derivative/polyethylene glycol

diacrylate photoinitiator system. It has excellent photo-bleaching performance, which is being employed for 3D light color printing for a long-wavelength light-emitting diode. However, searching for a new technique that can provide a better printing resolution has continued. In the current study, a novel 3D color printing technique that makes use of electron cloud spin projections has been proposed and manipulated. The microring circuit has the form of a panda ring, which has been used by many researchers for different applications. The advantage is that the nonlinear phase modulators can be adjusted to obtain the whispering gallery mode (WGM), which is suitable for the required applications.^{11–14} The WGM phenomenon has been used by different researchers for various applications.^{15,16} The electron cloud is the region where electrons are most likely to be localized. Many researchers have used the concept of controlling the electron spin for various applications.¹⁷ In this proposed technique, the nonlocalized electron propagation along the z-axis is also included to increase the printing resolution, and promising results have been obtained. The Optiwave program has been used for the simulation from which the parameters are extracted, and the MATLAB program makes use of the extracted parameters. The MATLAB program implements 3D quantum printing that uses electron cloud spin projections generated by the microring circuit.

2 | BACKGROUND

The electron has a quantum feature known as spin. The electron spins in 3D are considered.¹⁸ In the x-axis: spin-down $|\downarrow\rangle$ ($|01\rangle$), with the spin matrix is $\frac{\hbar}{2} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$. In y-axis: spin up $|\uparrow\rangle$ ($|10\rangle$), with the spin matrix is $\frac{\hbar}{2} \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$, and for the z-axis: the propagation axis, which is the probability of spin up or spin down, which is given by $C_1|\uparrow\rangle + C_2|\downarrow\rangle$. The probability of spin up is $|C_1|^2$, while the probability of spin down is $|C_2|^2$. Thus, the probability of spin up or spin down is $|C_1|^2 + |C_2|^2 = 1$, with the spin matrix $\frac{\hbar}{2} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$, where C_1 and C_2 are constants. $\hbar$ is the reduced Planck's constant. The superposition can be any of the two states, which is written as $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, with $|\alpha|^2 + |\beta|^2 = 1$.

The schematic diagram of the microring circuit is shown in Figure 1A, where the space source input is the dark soliton pulse,²² with the wavelength λ_1 as given in Equation (1) in terms of $\omega = 2\pi f$. Similarly, the modulated source is the Gaussian pulse with wavelength λ_2 as given in Equation (2). The fabrication structure is shown in Figure 1B, which consists of the silicon substrate, two silicon linear waveguides, a silicon microring at the center, with two nanorings at its sides. The center of the silicon microring is embedded with gold grating, which gives rise to electrons when illuminated

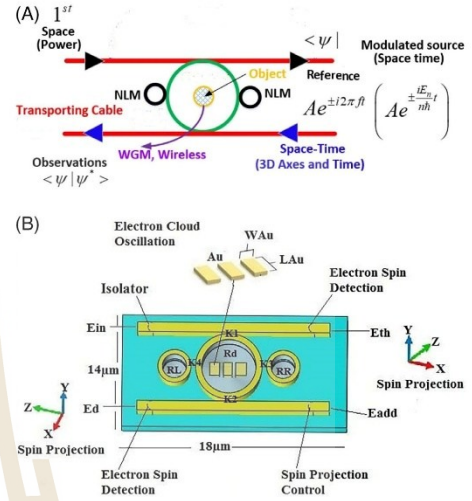


FIGURE 1 A, Schematic diagram of the 3D quantum printing circuit, where NLM is the nonlinear phase modulator, WGM is the whispering gallery mode. The first space power can be the soliton pulse at the input port, the modulated source can be the Gaussian pulse at the add port. B, The fabrication structure, where the input port, throughput port, add port, and drop port are E_{in} , E_{th} , E_{add} , and E_d , respectively. R_d , R_L , and R_R are the main ring radius, side ring radii, and coupling constants, respectively. The isolator and spin projection control are applied to protect the feedback and filtering purpose. The other symbols are given in Table 1 [Color figure can be viewed at wileyonlinelibrary.com]

by light and the behavior of the electrons described by the Drude model^{22,23} as written in an Equation (3).

$$\Psi = B e^{-i(\omega t + \frac{E_0}{\hbar} z)}, \quad (1)$$

where $B = \bar{B} \cdot \text{Tanh}\left(\frac{z}{T_0}\right) \exp\left(\frac{z}{2T_0}\right)$, which is the input field (dark soliton). $\bar{B}$ is the amplitude, z is the propagation distance, T is the propagation time of the soliton pulse, the length dispersion $L_D = \frac{T_0^2}{\beta}$, where T_0 is the initial propagation time, β is the propagation constant in linear and nonlinear terms.²⁴ ωt is the phase term of the multiplexing function, $\frac{E_0}{\hbar}$, $n = 1, 2, 3, \dots$

The multiplexed space-time applied into the system, which is given by an Equation (2).

$$E_{add} = A e^{\pm i \omega t} \quad (2)$$

where $\omega = 2\pi f$, $f = \frac{c}{\lambda_2}$, ω , f , and c are the angular frequency, linear frequency and speed of light in vacuum, respectively. D and t are the amplitude and time, respectively. The $\pm$ signs of the exponent term used for the full-time slot axis; the control time is given by $e^{\pm i \omega t}$ and $t = 0$ for the time domain.

$$\epsilon(\omega) = 1 - \frac{ne^2}{\epsilon_0 m \omega^2} \quad (3)$$

The relative permittivity defined by ϵ , electron charge defined by e , mass defined by m and electron density defined by n and angular frequency defined by ω . At resonance, the angular frequency becomes plasma frequency (ω_p) as written in Equation (4) as:

$$\omega_p = \left[\frac{ne^2}{\epsilon_0 m} \right]^{-1/2} \quad (4)$$

From Equation (4) the electron density $n = \frac{\omega_p^2}{e^2} \epsilon_0 m$. The plasmonic wave oscillation is a consequence of electron density in an electric field. To obtain the exponent decay and TM-polarization of the electric field Maxwell equations are employed.

The Bragg and resonant wavelengths are related by $\lambda_B = 2n_e \Lambda$, Bragg wavelength is λ_B , effective refractive index is n_e , which is also the refractive index of the gold gratings inside the waveguide and grating period is Λ . Kerr effect exists through the structure and it can be included in the $n = n_0 + n_2$, $I = n_0 + n_2$, P/A_{eff} equation. n is the refractive index, n_0 is the linear refractive index, n_2 is the nonlinear refractive index, I is the optical intensity, P is the optical power and A_{eff} is the structure effective mode core area. The two nanorings at the sides of the silicon microring act as phase modulators which control the whispering gallery mode at resonance and through the throughput and drop ports the normalized intensities are obtained. The normalized intensities of the system output written as¹⁴:

$$\frac{I_{\text{th}}}{I_{\text{in}}} = \left[\frac{E_{\text{th}}}{E_{\text{in}}} \right]^2 \quad (5)$$

$$\frac{I_{\text{drop}}}{I_{\text{in}}} = \left[\frac{E_{\text{drop}}}{E_{\text{in}}} \right]^2 \quad (6)$$

From Equations (5) and (6), the first apace function is a soliton input via an input port, while the second space-time function is input via the add port simultaneously. The successive filtering of the transmission circuit controlled by the two side ring coupling parameters, where the induced nonlinear effects coupled the center ring can give the resonance. Finally, the spin projection applied at the resonance condition at the drop port, while the throughput formed the reference port. The spins transport can apply using the WGM and throughput port output for long-distance transmission, in which the spin information transmits via the spin-waves into the transmission lines.

3 | RESULTS AND DISCUSSION

In the simulation, the schematic and fabrication structure is as shown in Figure 1.²⁵ The input light (dark soliton) fed into the system has a center wavelength of 1.50 μm via the

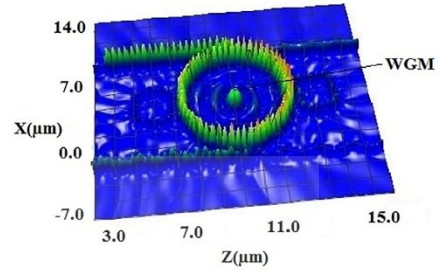


FIGURE 2 Results of the graphical output of the Opti-wave program, with the formation of the whispering gallery mode (WGM) at the center of the main ring of the microring circuit, where $R_d = 3.0 \mu\text{m}$, $R_R = 1.0 \mu\text{m}$, $R_L = 1.0 \mu\text{m}$, each $\kappa = 0.50$, Input power = 25 mW, with the center wavelength of 1.50 μm , and other parameters given in Table 1 [Color figure can be viewed at wileyonlinelibrary.com]

input port. The gold grating at the center ring is excited by the input light, where the Bragg wavelength formed. The oscillation of the polariton dipoles and plasmonic waves occurs. The generated whispering gallery mode is made possible from the coupling of light inside the microring with the embedded gold gratings at the center of the silicon microring. The center wavelength usually shifted by the gold grating to the Bragg wavelength. The device output ports are the throughput and drop ports, where the output signals are obtained. First, in the manipulation, the 32-bit version 12.0²⁶ of the Optiwave FDTD program is employed and at resonance with a particular wavelength results in the trapping of light inside the silicon microring. The grid size of the system using the Optiwave FDTD simulation is 0.05 with the mesh cell size of 399, 71, and 456 for the three axes (x, y, and z, respectively). The APML boundary condition which is the anisotropic perfect matched layer is used with a layer of 15, real tensor of 1.0 and 1.0×10^{-12} theoretical reflection coefficient. The number of round trips is 20 000 which is used to confirmed resonant results. A high-performance computer of 32Gb RAM used for all simulations to ensure accuracy. As shown in Figure 2 is the WGM formed at the center of the silicon microring using other parameters in Table 1. The parameters from the results of the Optiwave FDTD simulation are extracted and used in the MATLAB program. In Figure 3, the plot of the electron spins with the time function is shown, where the spin-up (blue) at the throughput port, spin-down (red) at the drop port, and no spin (green) at the throughput port/drop port. Figure 3A is the modulation wavelength of 1.40 μm with a projection time of 1.50 fs. Figure 3B is the modulation wavelength of 1.10 μm with a projection time of 1.40 fs, while Figure 3C is the modulation wavelength of 0.8 μm with a projection time of 0.8 fs. The spins of the electron in three axes (x, y, z) given by the following. The spin to the x-axis (spin-x), y-axis, and z-axis are the spin-down $|1\rangle$, spin-up $|0\rangle$, and no spin projection,

TABLE 1 The parameters that were selected and used in the simulation

Parameters	Symbols	Values	Units
Input power (Dark soliton)	P	1–25	mW
Input power (Gaussian pulse)	P	1–25	mW
Length of silicon linear waveguide	L	15.0	μm
Silicon center ring radius	R_d	3.0	μm
Left nanoring radius	R_L	1.0	μm
Right nanoring radius	R_R	1.0	μm
Gold dielectric constant ¹⁹	ϵ_o	6.9	
Gold permittivity ¹⁹	ϵ	10.0	
Gold width	W_{AU}	0.4	μm
Gold thickness	d	0.2	μm
Gold length	L_{AU}	1.6	μm
Refractive index of Au ¹⁹	n	1.80	
Insertion loss	γ	0.01	
Coupling coefficient	κ	0.50	
Refractive index Si ²⁰	n_{Si}	3.42	
Si nonlinear refractive index ²⁰	n_2	1.3×10^{-13}	$\text{m}^2 \text{W}^{-1}$
Input light wavelength input port	λ_1	1.50	μm
Modulation wavelength input	λ_2	1.40, 1.10, 0.80	μm
Waveguide core effective ²⁰	A_{eff}	0.30	μm^2
Waveguide loss	α	0.50	dB (cm)^{-1}
Plasma frequency ²¹	ω_p	1.2990×10^{16}	rad s^{-1}
Electron mass	m	9.11×10^{-31}	kg
Electron charge	e	1.6×10^{-19}	Coulomb
Permittivity of free space	ϵ_o	8.85×10^{-12}	Fm^{-1}
Grating period	Λ	0.50, 0.40, 0.30	μm
Reduced Planck's constant	$\hbar$	1.00	ARU

respectively. By using Equations (1-6), the dark soliton pulse excites the gold grating, which leads to electron cloud oscillations. It can process the spin-up, and spin-down by the projection automatically at the drop port. The output at the throughput port performed the referencing information. The center wavelength of 1.50 μm when modulated with the Gaussian pulse of 1.30, 1.10, and 0.80 μm the spin states of the electron can be detected and characterized. The normalized outputs are obtained at the throughput and drop ports. The electron cloud at the center system is of high density due to the intense optical power at the center WGM. Figure 3D is the selected plot of the 3D image ($\lambda = 1.50 \mu\text{m}$) with the time function, where the 3D image resolution and filtering were taken in account. Generally, the projection of the first space to the second space after the singularity is linked by time-bridge. The paradox pair (orthogonal components) has the shortest time of the paradox gap. After the measurement (disturbance), the time-bridge broken, the paradox pair collapsed. The shortest time of the paradox pair is

around 50 fs. It is the limitation of all measurements (observations). The resolution obtained with an angle of observation of 45° , making use of the relation as $t = (\frac{\pi m}{2c})$, where t is the resolution at each projection point, r is the radius of the microring, n is the refractive index of the silicon ring, and c is the speed of light in vacuum. The separation of each spin projection point in time of 50 fs (10^{-15} s) achieved. For the 3D image construction, the grating at the center of the microring with suitable parameters in Table 1 forms the WGM beam, which is projected upwards and with the trapped electrons at the center, the electron cloud oscillation that leads to spin-down (red) and spin-up (blue) projected at the x and y axes propagated along the z-axis (green) are superimposed to construct the 3D image. The image formed by the vortex beam of the spin electrons, which is the twisted beam of the angular momentum. It appears as a helix surrounding a propagation beam (z-axis), which is projected on the flat surface, where the 3D image is constructed. For filtering, the median filter employed to remove the noise from the 3D image to

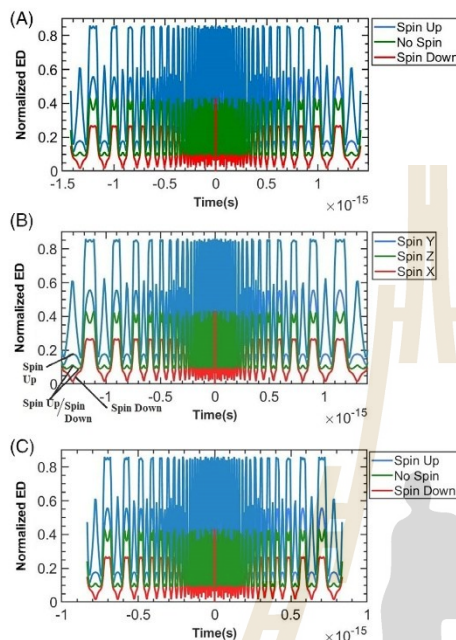


FIGURE 3 The plot of the Matlab program result using the time function where the spin-up (blue) at the throughput port, spin-down (red) at the drop port and spin-up/spin-down (green) at the throughput port/drop port, where A, the modulation wavelength of 1.40 μm with projection time of 1.50 fs; B, the modulation wavelength of 1.10 μm with projection time of 1.40 fs; and C, the modulation wavelength of 0.8 μm with projection time of 0.8 fs [Color figure can be viewed at wileyonlinelibrary.com]

enhance the 3D image quality. By using the MATLAB program, the filtering image by a 3×3 filter obtained. The trapped electron cloud distributed covering the gold grating at the center, which is in the form of WGM output. The electron transported sequentially in time to the projection target, which can be projected to the image plane, while the gap of the 2-spin projections filled by the non-spin along the propagation axis. In application, the electron cloud can be used to form a 3D shape (hollow), from which the 3D mold can be constructed and used for 3D printing. Moreover, this method is formed by the quantum network, which can also be applied by either wireless or cable transmission for long-distance transmission. By using the space-time control, where somehow the system can reach the teleportation when the space-time uncertainty saturation, which can also be very interesting and challenging for future technologies.

In operation, the microring embedded gold gratings circuit is used with an electron cloud spin projection to form the 3D image of the object at the center ring. A paradox pair

is formed by the wave-particle duality. After the projection, the measurement is observed. But the reality is disappeared, means the paradox pair is collapsed. The center ring radius is varied from 2 to 4 μm , where the results of 30, 50, and 70 fs scanning resolution are obtained by the ring radii of 2, 3, and 4 μm , respectively. The 3D image plot of these ring radii is shown in Figure 4A-C. The input light is the space source is fed into the system via the input port. The space-time source is multiplexed to form the space-time function at the add port. The input light (dark soliton) excites the gold gratings at the center ring, which leads to electron cloud oscillations that form the electron density results in the spin-up (y-axis) and spin-down (x-axis) of electrons, where both spins are propagating along the z-axis. The small rings at the side of the center ring act as phase modulators, induce the nonlinearity effect in the system. The trapped light oscillated around the microring inside the microring, the suitable parameters as given in Table 1. The trapped light forms the whispering gallery mode at the center ring, which is projected upwards and with the trapped electrons at the center ring where the spin-up (blue) (y-axis), and spin-down (red) (x-axis) propagating along the z-axis are superimposed to form the 3D image of the object at the center ring. Other works are cited in Table 2.

4 | CONCLUSION

A novel 3D quantum printing technique using a microring circuit has been proposed. The Bragg wavelength can be formed by the embedded gold grating which also induced polariton, which can be employed to form the plasmonic sensor and dipole oscillation. The electron cloud is driven by the polariton and generated in the form of the WGM beam, which can transport through the system via the space-time control carrier. The transport of the trapped electron densities within the circuit is made possible via wireless connection making use of the whispering gallery mode and via cable connection. The electron spins distinguished by the time sequence modulation and projection. By using the modulated sources with the Gaussian pulse of 1.30, 1.10, and 0.80 μm , the 3D images using the spin projections at the drop port obtained, in which the image projection space separation of 50 fs (10^{-15} s) is achieved. The 2-axes of the electron spins and the propagation axis use to form the image, where the 3D quantum printing can construct. In this study, the ground state of the electrons was only applied, which is described by the electron density. The errors were not taken in account since the errors have less effect on the quantum bits results. In application, a pan da-ring can form the plasmonic antenna and apply in a quantum computing device, quantum sensor, quantum encryption based on the spin projections, while the long-distance 3D image with quantum security via either cable or wireless is possible.

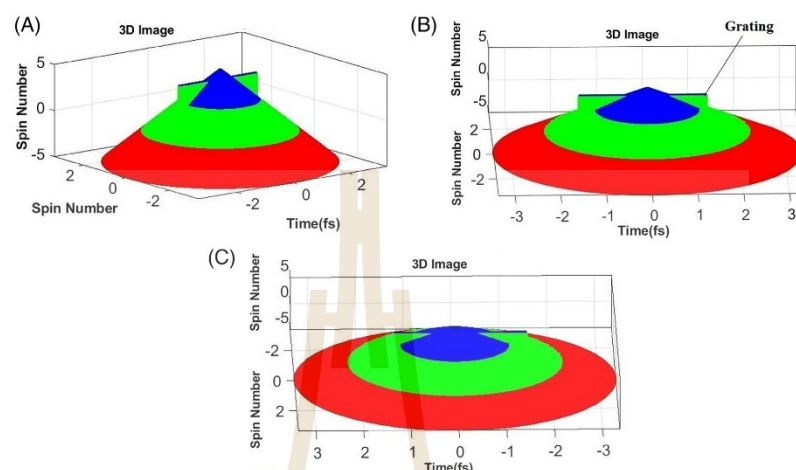


FIGURE 4 The 3D image plot ($\lambda = 1.50 \mu\text{m}$) using the electron transport spin projection with the modulation wavelength of $1.30 \mu\text{m}$, where A, ring radius of $2 \mu\text{m}$; B, ring radius of $3 \mu\text{m}$; and C, ring radius of $4 \mu\text{m}$ [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Comparison of print resolution of present study with previous study

Proposed work (scanning resolution)	Other works
30 fs	1 ms^{-1} [27]
50 fs	40 mm s^{-1} [28]
70 fs	8000 mm s^{-1} [29]

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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High-Gain InP-based hybrid plasmonic nanoantennas Design Using SiO₂-Graphene-Au Stacked Waveguide

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Abstract— In this study, we present the design and analysis of high-gain InP-based hybrid plasmonic nanoantennas incorporating a SiO₂-Graphene-Au stacked waveguide. The proposed nanoantenna leverages the superior optical properties of Indium Phosphide (InP), integrated with a hybrid waveguide structure consisting of SiO₂, graphene, and gold (Au). The inclusion of SiO₂ serves as a low-loss dielectric layer, graphene enhances light-matter interactions, and Au provides strong plasmonic effects. Our simulation results, obtained using CST, demonstrate that the proposed design achieves a significant enhancement in gain and directivity compared to traditional configurations. Specifically, the proposed nanoantenna exhibits a remarkable gain of 13.27 dB at a resonant frequency of 193.45 THz (1550 nm), highlighting its potential for high-performance photonic applications.

Keywords— Hybrid plasmonic nanoantenna, InP Based, SiO₂-Graphene-Au stacked waveguide, high gain, photonic applications.

1. INTRODUCTION

The rapid advancement of nanotechnology has significantly propelled the development of nanoscale devices with diverse applications. Among these innovations, Plasmonic nanoantenna waves are caused by the interaction of light at the interface between a dielectric and a metal material, known as surface plasmon polaritons (SPPs). Indium Phosphide (InP)-based nanoantennas have garnered considerable attention due to their unique optical and electronic properties. InP, a semiconductor material with a direct bandgap and high electron mobility, is ideal for photonic and electronic devices [1]. The integration of InP into nanoantennas enhances light emission and detection efficiency [2]–[5], which is crucial for highly sensitive sensors and efficient light-emitting devices. While silicon (based on Silicon on Insulator: SOI) remains widely used due to its mature technology and cost-effectiveness, InP offers superior performance in optoelectronic applications. InP's higher electron mobility, direct bandgap, and better infrared performance make it particularly suitable for high-frequency and high-performance photonic applications. These advantages can be fully leveraged in InP-based nanoantennas, ensuring their efficacy in advanced photonic devices. Recent research has extensively explored the use of InP in nanoantenna design, leveraging its advantageous properties to

create high-performance photonic devices. A significant focus has been on hybrid plasmonic designs, which aim to enhance the functionality and efficiency of these nanoantennas. These hybrid designs combine InP with plasmonic materials to achieve superior light manipulation and improved device performance. Arbel et al. explored the light emission rate enhancement from InP multiple quantum wells (MQW) by employing plasmon nano-antenna arrays. The study demonstrated that InP MQWs, when integrated with plasmonic nano-antenna arrays, could significantly enhance the light emission rate, making them suitable for highly sensitive photonic applications [2]. Nikoufard et al. investigated hybrid plasmonic nanoantennas with the capability of monolithic integration with lasers and photodetectors on InP substrates. This work highlighted the potential of InP substrates in achieving high-performance hybrid plasmonic devices that are capable of integrating multiple photonic components, thus enhancing overall device functionality [6]. Khodadadi et al. provided an analytical approach to studying a hybrid plasmonic waveguide-fed nanoantenna based on a new director design. This research focused on the integration of hybrid plasmonic waveguides with InP substrates to improve light guidance and emission efficiency, which is crucial for developing high-performance photonic devices [7]. Baranwal and Pathak designed an InP-based hybrid plasmonic inset-fed rectangular patch nanoantenna. Their design aimed at optimizing the antenna structure to achieve high gain and efficient light manipulation. The use of hybrid plasmonic materials in conjunction with InP substrates provided a pathway to significantly enhance antenna performance [8]. Soleimannezhad et al. discussed the development of low-loss InP-based hybrid plasmonic waveguides. Their study demonstrated that InP substrates, combined with hybrid plasmonic materials, could achieve low-loss waveguiding, essential for efficient light transmission and enhanced antenna gain [9].

However, despite these promising results, the achieved gain of InP-based hybrid designs as shown on Table I is still not as high as desired. Therefore, it is necessary to explore further design enhancements. One promising approach is the incorporation of a stacked waveguide structure [10], [11]. By integrating stacked waveguides with InP-based nanoantennas, it is expected that the unique properties of InP can be fully

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leveraged to significantly enhance antenna gain and overall performance. Therefore, in this study, we focus on incorporating SiO₂-Graphene-Au stacked waveguides to enhance the gain of the antenna. The choice of SiO₂, graphene, and Au in the stacked waveguide design is motivated by their complementary optical properties, which collectively contribute to superior light manipulation and emission characteristics. SiO₂ serves as a low-loss dielectric layer, providing a stable and transparent medium for light propagation. Graphene, with its remarkable electronic and plasmonic properties, facilitates strong light-matter interactions and supports high confinement of electromagnetic fields. Gold (Au), a well-known plasmonic material, further enhances the plasmonic effects, leading to increased local field intensities. The integration of SiO₂-Graphene-Au stacked waveguides with InP-based nanoantennas is expected to leverage the unique properties of InP substrates fully. InP, known for its excellent optoelectronic characteristics, provides a high-refractive-index contrast, essential for efficient light guidance and emission. By combining these materials, we aim to create a hybrid plasmonic structure that can significantly boost antenna gain and overall performance. To simulate the system, we utilized the CST program to analyze the plasmonic antenna's reflection coefficient (S_{11}), electric field distribution, radiation pattern and gain.

II. DESIGN AND ANALYSIS

The structure of the plasmonic nanoantennas presented in this study is meticulously engineered to leverage the unique optical properties of multiple materials, arranged in a layered configuration. The design as shown in Fig. 1 incorporates a micro-ring resonator integrated with a SiO₂-Graphene-Au stacked waveguide, built upon an InP (Indium Phosphide) substrate. The foundation of the nanoantenna structure is an InP substrate. Indium Phosphide is chosen for its high electron mobility and excellent optical properties, making it a suitable platform for photonic applications. The substrate has a significant impact on the optical confinement and propagation characteristics of the nanoantenna. Above the InP substrate, an InGaAsP (Indium Gallium Arsenide Phosphide) layer is deposited. This material is commonly used in photonic devices due to its tunable bandgap and compatibility with InP substrates. The InGaAsP layer aids in the efficient confinement and guiding of optical modes within the nanoantenna structure. A silicon layer is placed above the InGaAsP layer. Silicon is a key material in photonic circuits due to its high refractive index, which provides excellent optical confinement. This layer forms the core of the micro-ring resonator, which is integral to the operation of the nanoantenna. An insulating layer of silicon dioxide (SiO₂) is deposited on top of the silicon layer. SiO₂ is used to electrically isolate the silicon layer from the subsequent graphene layer, preventing any undesired electrical interactions that could affect the optical performance.

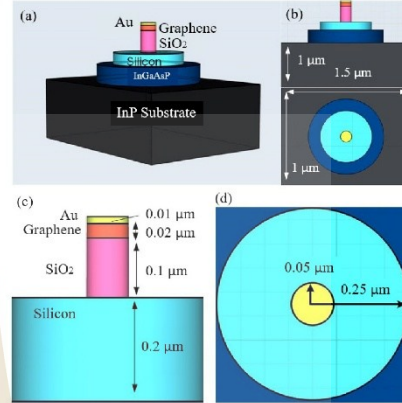


Fig. 1. The structure of the InP-based hybrid plasmonic nanoantenna with SiO₂-Graphene-Au stacked waveguide and its dimensions in micrometer scale: (a) Isometric view; (b) Side and top views; (c) Stacked waveguide; (d) Stacked waveguide top view.

Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, is positioned above the SiO₂ layer in the nanoantenna design. Renowned for its exceptional electrical and optical properties, graphene exhibits high carrier mobility and tunable optical conductivity. Within the context of the nanoantenna, graphene significantly enhances the plasmonic response and facilitates dynamic tuning of the antenna's optical characteristics. The topmost layer of the nanoantenna is composed of gold (Au), selected for its superior plasmonic properties that are essential for achieving high field enhancements. The gold layer interacts synergistically with the graphene and silicon layers, supporting surface plasmon resonances and thereby enhancing the overall performance of the nanoantenna. In designing the nanoantenna, the resonance frequency and wavelength were meticulously selected based on their critical importance to optical communication. Typical wavelengths used in optical communication systems are 1550 nm, 1310 nm, and 850 nm, corresponding to frequencies of 193.45 THz, 229 THz, and 352.9 THz, respectively. These specific wavelengths are chosen primarily due to their low-loss characteristics, which are crucial for efficient signal transmission and minimal attenuation over long distances. Our proposed nanoantenna design is optimized to operate at the optical communication wavelength of 1550 nm. This particular wavelength is favored because it falls within the region of the optical spectrum where fiber optic communication systems experience the least amount of signal loss. By targeting this wavelength, our nanoantenna can achieve high efficiency and performance, making it ideally suited for advanced photonic applications where maintaining signal integrity and minimizing losses are of paramount importance.

III. SIMULATED RESULTS AND DISCUSSION

The analysis of the S_{11} parameter for the high-gain InP-based hybrid plasmonic nanoantenna with a SiO₂-Graphene-Au stacked waveguide is presented in Fig. 2. The analysis focuses on the frequency range where $S_{11} < -10$ dB, indicating effective resonant behavior. The configuration with the InP substrate and InGaAsP ring (black line with square markers) exhibits a resonant frequency at approximately 192.75 THz, with S_{11} dipping to a minimum of about -17 dB. In contrast, the proposed design with the SiO₂-Graphene-Au stacked waveguide (red line with circular markers) shows a resonant frequency shift to the 193.0-194.5 THz range, with a minimum S_{11} value of around -14 dB at 193.45 THz. This shift demonstrates the effectiveness of the stacked waveguide in enhancing the nanoantenna's performance, aligning with the desired resonant frequency range for the intended application.

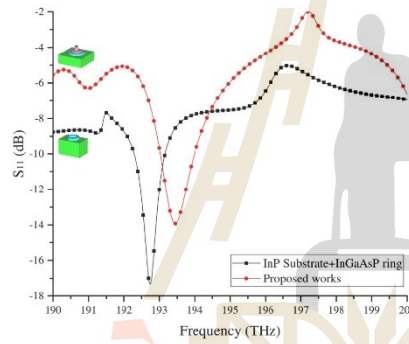
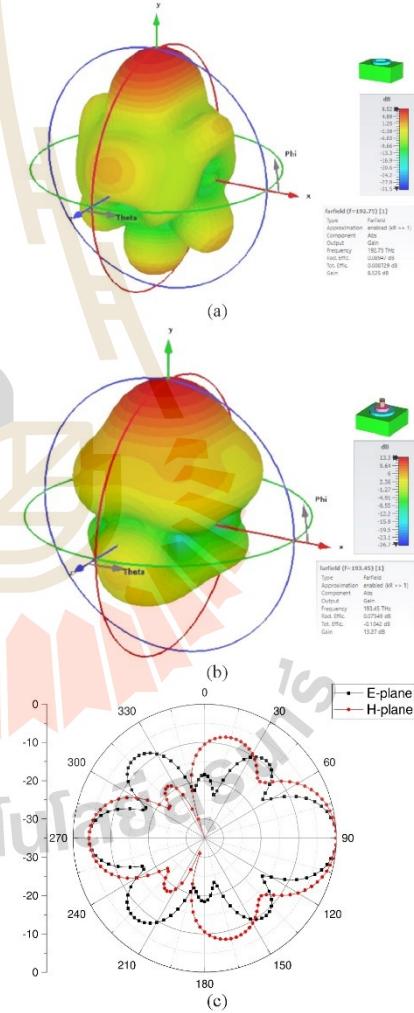


Fig. 2. The S_{11} parameter comparison of the InP-based hybrid plasmonic nanoantenna.

The radiation patterns for the InP-based hybrid plasmonic nanoantenna at the identified resonant frequencies are shown in Fig. 3. The analysis focuses on the results for both the initial configuration (InP substrate with InGaAsP ring) and the proposed design (adding SiO₂-Graphene-Au stacked waveguide). At 192.75 THz, the initial configuration exhibits a relatively isotropic radiation pattern, as seen in Fig. 3(a), with a gain of 8.525 dB. The radiation and total efficiencies are 0.09487 and 0.008729, respectively. This pattern indicates effective radiation in multiple directions with a broad main lobe. In contrast, the proposed design at 193.45 THz shows a more directional radiation pattern, depicted in Fig. 3(b), with an enhanced gain of 13.27 dB. The radiation and total efficiencies are 0.07549 and -0.1042, respectively. This pattern highlights a narrower main lobe, suggesting a more focused radiation direction, which is advantageous for specific applications. The polar radiation patterns for the E-plane and H-plane at the respective resonant frequencies further illustrate these differences. The initial configuration, shown in Fig. 3(c), has multiple lobes with moderate directivity in the E-plane and a consistent but lower intensity

lobe structure in the H-plane. Conversely, the proposed configuration, seen in Fig. 3(d), displays more pronounced and intense lobe structures in both planes, indicating increased directivity.

In summary, the proposed SiO₂-Graphene-Au stacked waveguide configuration demonstrates significant improvements in gain and directivity at 193.45 THz (1550 nm) compared to the initial InP substrate with InGaAsP ring configuration. These enhancements underscore the effectiveness of the proposed design in enhancing the radiation characteristics of the nanoantenna, making it more suitable for high-gain applications.



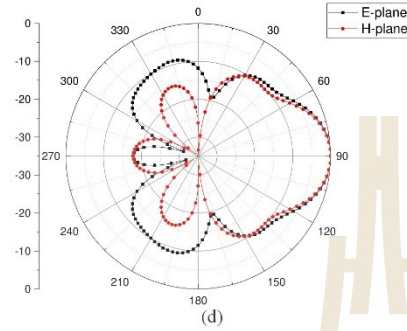


Fig. 3. The radiation pattern comparison of the InP-based hybrid plasmonic nanoantenna: (a) 3D of structure without stacked waveguide; (b) 3D of the proposed work; (c) 2D of structure without stacked waveguide; (d) 2D of the proposed work.

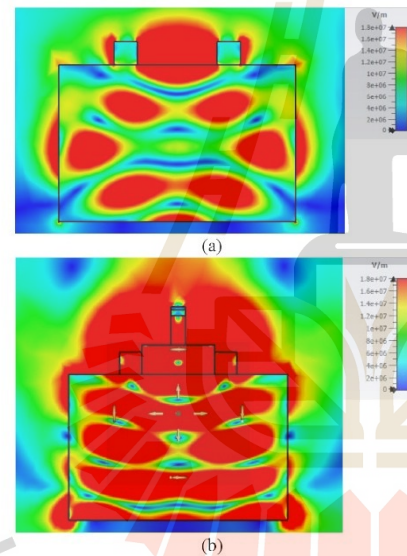


Fig. 4. The electric field distribution comparison of the InP-based hybrid plasmonic nanoantenna: (a) InP-based structure without stacked waveguide; (b) The proposed work.

The electric field distribution for two different configurations of InP-based hybrid plasmonic nanoantennas is illustrated in Fig. 4. Fig. 4(a) depicts the distribution for the InP-based structure without a stacked waveguide, while Fig. 4(b) shows the distribution for the proposed design incorporating a SiO₂-Graphene-Au stacked waveguide. In the InP-based structure without the stacked waveguide, the electric field appears less concentrated and more diffuse. This indicates a lower efficacy in confining electromagnetic fields, which may lead to suboptimal performance in enhancing light-matter interactions.

Conversely, the proposed design with the SiO₂-Graphene-Au stacked waveguide demonstrates a significantly higher concentration of the electric field in specific regions. This enhanced confinement suggests superior performance in terms of light-matter interactions, indicating the effectiveness of the stacked waveguide in improving the overall functionality of the nanoantenna. This enhanced confinement suggests a superior performance, potentially resulting in improved optical properties and a higher degree of light-matter interaction. In contrast, the proposed design with a SiO₂-Graphene-Au stacked waveguide demonstrates a remarkable gain of 13.27 dB at a resonant frequency of 193.45 THz (1550 nm), as shown in Table I. This significant improvement in gain underscores the effectiveness of incorporating the SiO₂-Graphene-Au stacked waveguide into the InP/InGaAs framework. The synergistic effects of these materials contribute to enhanced light manipulation and emission characteristics. The analysis of Fig. 4 and Table I highlights the advantages of the proposed SiO₂-Graphene-Au stacked waveguide design for InP-based hybrid plasmonic nanoantennas.

TABLE I. THE COMPARATIVE PERFORMANCE OF VARIOUS INP-BASED HYBRID PLASMONIC NANOANTENNA DESIGNS

Ref.	Combined Material	Shape/Design	Resonant Freq. or WL	Gain (dB)
[2]	InP/InGaAs + Au	Au single/double-strip antenna	1360nm/1540nm	3.2/4
[5]	InP n ⁺ /InP n ⁻ /Ag or Au	Monolithic Integration	180 to 220 THz	9
[6]	InP/InGaAs + Au	Rectangular Patch	1550nm (193.4THz)	6.78
[7]	InP/InGaAs /InP/Au	InP-based hybrid	193.5 THz (1550 nm) and 229 THz (1310 nm)	3.6 and 1.1
[8]	InP/InGaAs /InP/Au	InP-based hybrid	1.55 μ m	-
This work	InP/InGaAs -Stacked waveguide	SiO ₂ -Graphene-Au Stacked Waveguide	193.45 THz (1550 nm)	13.27

The superior electric field confinement and the significantly higher gain achieved by the proposed design underscore its potential for high-performance photonic applications. The integration of SiO₂, graphene, and Au with InP/InGaAs not only enhances optical properties but also demonstrates the feasibility of achieving substantial improvements in nanoantenna performance. This integration leads to a more efficient light-matter interaction, resulting in a higher degree of optical enhancement and a broader range of photonic applications. For instance, such high-gain nanoantennas can be employed in advanced optical communication systems, where their superior performance can significantly improve data transmission rates and signal clarity over long distances. Additionally, these nanoantennas can be utilized in highly sensitive sensors for biomedical

applications, enabling more accurate detection of biological markers and improving diagnostic capabilities. Furthermore, they can enhance the performance of photonic integrated circuits, contributing to the development of more compact and efficient optoelectronic devices. These applications demonstrate the versatility and impact of the proposed SiO₂-Graphene-Au stacked waveguide design in advancing current photonic technologies.

IV. CONCLUSION

In conclusion, this study successfully demonstrates the significant advantages of incorporating a SiO₂-Graphene-Au stacked waveguide into InP-based hybrid plasmonic nanoantennas. The proposed design exhibits a substantial enhancement in gain and directivity, achieving a peak gain of 13.27 dBi at a resonant frequency of 193.45 THz. This superior performance is attributed to the synergistic effects of the integrated materials, which collectively enhance light confinement and manipulation. These findings underscore the potential of the proposed nanoantenna for advanced photonic applications, particularly in scenarios requiring high efficiency and focused radiation. For example, the high-gain and enhanced directivity make these nanoantennas ideal for use in optical communication systems, where they can significantly improve data transmission rates and signal integrity. Additionally, their application in biomedical sensors could lead to more precise and sensitive detection of biological markers, enhancing diagnostic capabilities. Future work will focus on further optimizing the material properties and structural configurations to achieve even greater performance improvements. This may include exploring alternative materials and novel structural designs that can provide even higher levels of light confinement and manipulation, thereby expanding the range of potential applications and further advancing the field of photonic technology.

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