Plasmonic devices for on-chip optical interconnects

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Plasmonic Devices for on-Chip Optical Interconnects

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*A Dedication to My
Parents*

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Kelvin Ooi Jian Aun

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Abstract

Continuous scaling of electronic integrated circuits requires the replacement of electrical interconnects with optical interconnects. However, photonic optoelectronic devices are generally large in size, hence hindering smooth electronic–photonic integration. Plasmonics, which allows manipulation of light at the subwavelength scale, would be the key technology to provide the integration platform. Hence, in this research, we have designed plasmonic optoelectronic devices for on-chip optical data transmission on electronic–plasmonic–photonic integration platforms.

The first device developed is a monopole antenna-assisted waveguide-coupled cavity detector, which consists of a monopole antenna mounted onto the metal layer of the hybrid plasmonic waveguide end and separated by a feed-gap which forms the detector cavity. The detector has an absorption volume of as small as $220 \times 150 \times 60 \text{ nm}^3$ and optical power absorption as high as 42%. To our best of knowledge, this is the first waveguide-coupled monopole antenna-assisted cavity detector design. The design offers several practical benefits such as full waveguide-integration and CMOS compatible fabrication process.

For the second device, we have continued to enhance the previous detector's absorption efficiency to 78% by designing plasmonic coupled-cavities, which consists of coupler, detector and reflector cavities arranged in series. The plasmonic coupled-cavities show strong inter-coupling between the three cavities, and hence increase optical power coupling and localization inside the detector unit.

Abstract

The third device we have designed is an ultracompact vanadium dioxide (VO_2) dual-mode plasmonic waveguide electroabsorption modulator, which shows low insertion losses of $\sim 1\text{dB}$, high modulation depths of $\sim 10\text{dB}$, with ultrashort modulation lengths of $\sim 200\text{nm}$. The modulator has a potentially ultrafast operating speed and low energy consumption of $\sim 2.6\text{fJ/bit}$. The high performance is attributed to the use of a mode-switching operation to switch between a low loss hybrid plasmonic mode and high loss MIM mode, enabled by its unique metal–insulator– VO_2 –insulator–metal (MIVIM) structure.

Finally, we have explored doped graphene nanoribbons (GNRs) to build ultracompact active waveguide modulators and optoelectronic devices for mid-infrared operating wavelengths. Graphene surface plasmons are shown to compress mid-infrared wavelengths down by up to two-orders. We have built GNR plasmonic waveguide modulators that show modulation contrasts exceeding 30dB , which are further extended to build GNR active power splitters. The GNR active power splitters are potentially scalable to large and complex active multi-port networks. This opens up a potential possibility of building mid-infrared integrated circuits that operate in deep submicron dimensions.

The design of these plasmonic optoelectronic devices may bring forth the realization of practical electronic–plasmonic–photonic integrated circuits, owing to the much reduced device sizes and substantial reduction of energy consumption. In addition, most of the devices can be fabricated by largely CMOS compatible processes, thus making industrial realization possible in the near future.

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Introduction

The continuous downscaling of CMOS transistors has improved the performance of integrated-circuits in terms of increased compactness and functions. However, the continuous scaling down of the electrical interconnects has hit a great bottleneck as shrinking dimensions increases power dissipation and RC delay. Optical interconnects have been proposed as the replacement for electrical interconnects by virtue of their low propagation loss, high speed transmission and high bandwidth. However, photonic devices that interface between electronic transistors and optical waveguides are immense in size due to the diffraction limit, and hence hinder good electronic–photonic integration. In contrast, plasmonic devices are able to manipulate light in the subwavelength scale, thus allowing us to build miniature optoelectronic devices, forming the building blocks for next-generation electronic–plasmonic–photonic integrated nanocircuit technology. Hence, we propose plasmonics as the key technology to provide the integration platform.

1.1 Motivation

1.1.1 Electrical and optical interconnects

Moore’s law, a term coined by Carver Mead in the 1970s, describes the trend of the number of transistors that can be placed in an integrated circuit doubling every two years. However, this trend is not without limits. As CMOS circuits scale down to the sub–100nm regime, we begin to see physical effects like drain-induced barrier lowering in the CMOS [1].

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Even as the quantum limit of CMOS scaling has not yet been breached, there are already a number of obstacles preventing the increase in speeds of electronic devices. The current most significant issue is the electrical interconnect bottleneck. As electrical interconnects scale down, a variety of problems become apparent such as line resistance, wave reflections, crosstalk and thermal distortions, skin effects and RC delays [1, 2]. Interconnect delays become the major hindrance of bandwidths reaching beyond 10Gb/s and chip scaling down to the sub-100nm level.

One promising candidate interconnect technology emerged in the past two decades that might replace the electrical interconnect – the optical interconnect. In a review paper [3], Miller provided a comprehensive analysis of the advantages of silicon optical interconnects as a solution to the myriad of downscaling issues faced by the electrical counterpart. Firstly, there is minimal distance-dependent signal distortion and optical loss in silicon optical interconnects, essentially none if the operation wavelength is around 1550nm in the region of the transmission window of silicon material. Secondly, the inherent speed of transmission is very fast, at a substantial fraction of the velocity of light (depending on the effective index of the interconnect structure). Thirdly, optical transmission can also avoid a lot of problems involving wave reflections and impedance matching due to available anti-reflection and resonant techniques otherwise not possible in electrical transmission. Optical transmission does not suffer from thermal delay issues, unlike electrical transmission where, taking copper for an example, the resistivity changes by 40% over 100°C which ultimately affects the RC propagation delay. On top of that, there is potentially lower power dissipation as well.

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However, while the performance of optical interconnects in data transmission speed and capacity can continue to scale according to Moore's law, the downside is that it scales poorly in terms of size. The fundamental size limit of optical waveguides and optoelectronic components are governed by the law of diffraction, where the minimum size can be no less than half the optical wavelength. This is one of the main reasons why optical data transmission is still not ready to completely replace the electrical mainstay in data transport architecture, albeit having evident advantages in terms of speed, large data carrying capacity and design simplicity.

Amidst the continual debate around the future direction of chip interconnect technology, a game-changer emerged as recent as 10 years ago that might put up a whole new perspective in chip development. "Plasmonics", a term purportedly coined in 2000, has the potential to marry both the advantages of speed in optics and size in electronics [4]. This new device technology is able to exploit the unique optical properties of nanoscale metallic structures to manipulate light at the nanoscale.

1.1.2 Plasmonics

Plasmonics is a general term applied to the study of surface plasmons [5]. From a historical perspective of plasmonics, although mentioned previously that the term is coined as recently in 2000, the applications are, however, not at all new. Instances of plasmonic applications can be traced back to as early as the 4th century Byzantine era, where the concept of plasmonics is used in the crafting of the Lycurgus cup (a glass cup that appeared in different colors when illuminated with transmitted or reflected light due to the embedded gold nanoparticles), and also the staining of glass windows

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in medieval churches [6]. The work of Gustav Mie in 1908 on optical scattering of a metallic sphere is also closely related to surface plasmon resonance [7].

Specifically for a metal–dielectric interface, the plasmons are confined tightly to the surface of the metal and can interact strongly with photons to result in a polariton. The existence of surface plasmons are first predicted by Ritchie in 1957 [8], and they can be excited either by using electron bombardment (Ritchie, 1957) or by evanescent light wave coupling using the Otto [9] or Kretschmann [10] prism coupling configurations (1968). More recently, other excitation schemes are explored including grating coupling [11], or for more relevance to optoelectronics and interconnects, fiber coupling can be used [12].

The surface plasmon polaritons (SPPs) can be viewed as a special type of electromagnetic wave that travels parallel to the metal-dielectric interface. There are essentially 2 types of SPPs: the long-range SPP (LRSPP) which has high propagation ability, and the localized SPP (LSPP) which are non-propagating and tightly confined within “resonant” metal nanostructures. Both have their respective usage in optoelectronics: the former is employed as data carriers in plasmonic interconnects, while the latter is used mostly for optical power detection, modulation and other kinds of data processing requirements. In the field of chip technology, the most important advantage of plasmonics is the ability to “squeeze” light in nanoscale architectures with volumes smaller than the diffraction limit. The high energy confinement of plasmonic structures causes effective mode length to drop well below $\lambda_0/2$.

Significant progress of plasmonics has been made in various areas of optoelectronic integration. We see an explosion of research to develop plasmonic light

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sources [13], waveguides [14], detectors [15], and modulators [16] that operates in device dimensions far below the diffraction limit. Plasmonic devices are expected to get even more robust and efficient in the next few years owing to such immense research interest vested in them.

1.1.3 Plasmonic waveguide devices

The plasmonic waveguide borrows heavily from the prior understanding of the microwave waveguide. It can be understood and analyzed by either using traditional transmission line theory or optical transmission theory. As opposed to dielectric waveguides where the optical energy is confined within a high-index core surrounded by low-index cladding, plasmonic waveguides confine the light to metal–dielectric interface due to the negative dielectric permittivity-functions of metals.

Traditionally there are two types of plasmonic waveguides: the metal–insulator–metal (MIM) structure and the insulator–metal–insulator (IMI) structure waveguides [17]. Both types of waveguide geometry have their own distinctive advantages and disadvantages respectively. For instance, the MIM waveguide has higher optical power confinement ability but poor propagation lengths, while for the IMI waveguide it is the other way round. Both propagation length and confinement factor are qualities important to the plasmonic waveguide, as large propagation lengths can facilitate long range data transmission while high confinement factor can reduce the waveguide dimensions.

The tradeoff between propagation lengths and confinement has always been an unresolved issue for engineers to choose either the MIM or IMI geometry when constructing plasmonic waveguides. Nevertheless, a new class of plasmonic

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waveguide is introduced by Zhang's group in 2008 – the hybrid plasmonic waveguide [14] – which represents a compromise. The hybrid plasmonic waveguide consists of a low-index dielectric layer sandwiched in between a metal and high-index dielectric layers. In their experiments they observed that for certain nanowire and gap critical geometries, the optical mode is no longer photonic or SPP – instead, a new hybrid mode (a superposition mode consisting of cylinder modes of the nanowire and SPP modes of the dielectric gap, as described by the authors) emerged that exhibits characteristics of both strong confinement and long-range propagation. The authors claimed that hybrid plasmonic waveguides outperform the conventional plasmonic waveguides with a performance metric of 40–150 μm propagation lengths with corresponding $\lambda^2/400$ – $\lambda^2/40$ subwavelength mode confinements. Plasmonic waveguide performance is expected to continue to improve in the near future that will lead to industrial realization on the chip.

At the current stage, the propagation performance of plasmonic waveguides is still low when compared to photonic waveguides, and as such photonic waveguides are still preferred for data transmission. However, plasmonic waveguides will find important applications in various high performance plasmonic optoelectronic devices that we are going to design.

1.1.4 Optoelectronic transducers: the optical detector and modulator

A fresh engineer firstly introduced to the field of optical computing would definitely ask: since the development of optical interconnects have been met with great success, isn't the next logical step to develop optical transistors? This question is not without its merits: the idea of the optical transistor is always the dream of computer engineers

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to develop a transparent light-controlling-light machine, a perfect migration from the “ancient” electronic computing schemes. The advantages are myriad, but of foremost importance is the seamless integration with the fiber optics infrastructure now already ubiquitous in the telecommunications sector.

However, the current state of optical transistor research and development is all but rosy. In a 2010 Nature Photonics review article [18], Miller illustrated six essential qualitative criteria for optical transistors to be realized practically: so far nearly all proposals (in ref. [18] and references therein) fail those criteria. The six qualitative criteria laid out by Miller are: cascadability, fan-out, logic-level restoration, input/output isolation, absence of critical biasing, and logic level independent of loss. And even if all the qualitative criteria are met, there is still the need of sufficient quantitative performance (i.e. power requirements and operating speeds) to make adoption of the optical transistor more attractive than the current CMOS electronic transistor. For the record, the energy of operation and inherent speed of current CMOS silicon devices are at femtojoule and femtosecond per bit level respectively, and this means the optical transistor would need to at least reach those figures in order to be considered as a better alternative.

Since electronic transistors are still projected to be the mainstay of processor technology in the near future, integration schemes with optical interconnects will be necessary to exploit the best of both worlds. Obviously, the communication between electronic and optical signals has to be provided by optoelectronic transducers. These transducers are familiarly known as the optical detector and modulator.

Figure 1.1: Schematic of the roles of the optical modulator and detector in optoelectronic transduction for data transmission over an optical waveguide.

Figure [1.1](#) is a description of how optical modulators and detectors support the integration between electronic transistor logic processing and optical data transmission. A light source is the data carrier that travels to the modulator. The modulator, upon receiving electrical signals from the electronic transistor, either transmits or reflects/absorbs the light, to represent binary 1 or 0 respectively. The light output from the modulator is thus a series of pulses of relative high and low intensities representing a string of binary data that travels down the optical waveguide. A detector will pick up the optical binary signals and convert them back to electrical signals.

There are a few requirements needed for the optical detector and modulator to function efficiently. For the optical detector, some basic requisites include high speed response to match the frequency of the electric pulse, high responsivity and quantum efficiency. For the optical modulator, it needs to have a bandwidth high enough to match the electrical signal frequency input, large contrast to distinguish between high and low output signals, short modulation length and low insertion loss. For both devices, the essential improvements are the small footprint of the device, low power consumption and high speed capability as spelt out by the Moore's law. Existing

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photonic optoelectronic transducers do not meet these requirements, especially in the aspects of size, operating bandwidth and energy consumption. We would thus explore new device designs from the approach of plasmonics and also using new optical materials and device structures.

1.1.5 The CMOS compatible plasmonic optoelectronic devices

For electronic–plasmonic–photonic integration on a chip, it is always good to take care that the fabrication process of the plasmonic and photonic platforms can meet the CMOS technology standard.

The first and of foremost importance is the material choice to be used in the plasmonic device, especially the metals, as we would want to minimize the risk of contamination in the foundry. As such, non-CMOS compatible metals, like gold and silver (which are favourites in the field of plasmonics) are avoided in our study. Instead, we focused more on the metals which gives a good performance in the 1550nm wavelength regime and are also CMOS compatible, for example, aluminium and copper [70–72].

Also, we have to take care that the plasmonic devices can be fabricated by standard CMOS processes, for example, using lithography, deposition, etching, etc. As such, our plasmonic devices are designed to be planar, and features are producible by lithography, etching, and metal deposition. Irregular structures are avoided.

Fortunate for us, the progress of CMOS technology (which can be found in the annual ITRS reports, <http://www.itrs.net>) has offered many advantages in the realization of our plasmonic devices. For example, the semiconductor industry has progressed to the 14nm technology node, a resolution which is enough to fabricate the

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plasmonic devices' active volume dimensions in Chapter 2 – Chapter 4 (60nm×150nm for the plasmonic detectors, and 50nm×200nm for the plasmonic modulator). Besides, the recent introduction of high-K materials (e.g. HfO₂) has allowed the bias-voltage requirements to be decreased, with reduced power consumption as an added benefit.

1.2 Research objectives

This research aims to develop efficient plasmonic optoelectronic devices for the purpose of electronic–plasmonic–photonic integration. Design of the devices is carried out through the application of electromagnetic theories from literature as well as three-dimensional, full-wave simulations of device structures using CST Microwave Studio (versions 2010–2012).

The research aims to develop a plasmonic detector which has:

- a small device footprint
- high responsivity
- high speed response
- low required bias voltage

The research aims to develop a plasmonic modulator which has:

- a small device footprint
- short modulation length
- high extinction ratio
- high speed modulation
- low power consumption
- low insertion loss

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Besides the requirements laid out for both devices, fabrication steps and materials that are compatible to the CMOS process are also taken into consideration as a factor to translate device design and conception into industrial realization, although it is not strictly a requirement.

1.3 Major milestones

The major milestones of this research include the development of four types of plasmonic optoelectronic devices:

- I. The design of a compact waveguide-integrated monopole antenna-assisted plasmonic cavity detector. To the best of our knowledge, it is the first monopole antenna design for waveguide-integration as all previous waveguide-coupled plasmonic detectors are dipole antenna-based. The proposed plasmonic detector achieved optical power absorption of 42%, and has an active volume of $220 \times 150 \times 60 \text{ nm}^3$ – which is 3-orders smaller than current photonic detectors.
- II. The design of a plasmonic coupled-cavity system for enhanced surface plasmon localization in the plasmonic cavity detector. The plasmonic coupled-cavity system consists of a coupler cavity, detector cavity and reflector cavity arranged in series. The system displays strong inter-coupling between the three cavities, enhancing the optical power absorption to 78%.
- III. The design of an ultracompact vanadium dioxide dual-mode plasmonic electroabsorption waveguide modulator. The modulator uses vanadium dioxide (VO_2), a Mott insulator, as its active switching material. The metal–insulator– VO_2 –insulator–metal (MIVIM) structure design enables the

modulator to utilize the mode-switching operation, switching between a low-loss, hybrid plasmonic mode in the “on” state and a high-loss, MIM mode in the “off” state. The modulator shows a low insertion loss ($\sim 1\text{dB}$) and high modulation depth ($\sim 10\text{dB}$) with ultrashort lengths ($\sim 200\text{nm}$), and consumes energy of only 2.6fJ/bit .

- IV. The design of active graphene nanoribbon (GNR) waveguide modulators and switching devices. The large voltage-controlled tunability of graphene’s permittivity-function and extreme surface plasmon confinement are leveraged to build ultracompact mid-infrared active GNR plasmonic devices. A GNR waveguide plasmonic modulator that has modulation contrast exceeding 30dB is shown. The GNR waveguide plasmonic modulator is implemented into active GNR cross-junction waveguide power splitters, which scale easily into large arrays of active GNR waveguide networks.

1.4 Simulation methodology

All devices presented in this thesis are simulated using CST Microwave Studio (www.cst.com), versions 2010–2012. Most of the devices are simulated in the time-domain solver using hexahedral meshing, except the ring resonator in [Chapter 4](#) and graphene nanoribbon waveguides in [Chapter 5](#) are simulated in the frequency-domain solver using tetrahedral meshing due to their curvature and irregular aspect ratio respectively. For small structure dimensions (typically $< 100\text{nm}$), a step meshing of 5nm is used. For larger dimensions (typically $> 100\text{nm}$), the step meshing is relaxed to 10nm to save on simulation resources. For even larger dimensions (typically $> 1000\text{nm}$), the default setting is used, which is a step meshing of $\lambda/10$. When unsure of

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which step meshing to be used, the adaptive meshing and convergence test feature in CST is a good utility to assist in our decision.

Excitation signals in the device structures are provided by waveguide ports. By default, each waveguide port injects a 1W Gaussian optical power signal into the structure. For boundary conditions, wherever possible, open boundary with added spaces surrounding the structure and matching PML layers are used. For some cases, when the boundary has to be placed along a metal, then electric or magnetic boundaries are used.

The raw simulation result obtained is usually in form of the optical power pointing vector along every point in the simulation domain. Interpretation of the results would vary for each device type. More details will be given in the respective chapters.

1.5 Content organization

This report is organized into 6 chapters. In [Chapter 1](#), the optical interconnect is introduced as a potential replacement for the copper interconnect. A brief review of plasmonics and its uses in designing optical interconnects and optoelectronic components are discussed. The research objectives of designing more efficient plasmonic detectors and modulators are presented. The major milestones achieved in the course of the research are briefly summarized.

In [Chapter 2](#), the plasmonic detector and its current state-of-the-art research in literature are introduced. A new design based on a monopole antenna-assisted waveguide-integrated cavity detector is proposed to further boost the efficiency of the detector. Principles of the detector design are derived from the physics of antenna

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theory and cavity resonance. Simulation results are shown and compared to analytical formulation. Some fabrication issues are also discussed to streamline with available industrial processes. The design advantages are highlighted in terms of its absorption efficiency performance and also its fabrication ease and compatibility compared to previous designs.

In Chapter 3, the performance shortfalls of the monopole antenna-assisted cavity detector are investigated and avenues to improve them are explored. A coupled-cavity system is proposed to enhance the surface plasmon localization inside the detector cavity. Designs of additional coupler and reflector cavities are discussed in theory and optimized through simulation studies. The effect of strong cavity-coupling is shown to be present in this system, which translates to a greater enhancement of absorption efficiency than expected.

In Chapter 4, VO_2 is introduced as a potentially efficient switching material, in terms of its high switching contrast, acceptable switching field threshold, and ultrafast switching speed. Then, the implementations of VO_2 in a simple waveguide electroabsorption modulator and also a ring resonator modulator are briefly discussed. More focus is put on the discussion of a novel dual-mode waveguide modulator design using VO_2 as its core switching material. The large switching contrast of the VO_2 refractive index and extinction coefficient, combined with a hybrid plasmonic waveguide design, is leveraged for the dual-mode switching scheme, going beyond traditional designs of phase or absorption modulation schemes. It is shown that the dual-mode design combined both modulation schemes, enabling the device to switch between low-loss hybrid plasmonic modes and high-loss MIM modes, on top of switching between low and high extinction coefficients. The switching performances

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of different VO₂ waveguide modulators are compared in terms of insertion losses, modulation depths, figure-of-merit ratios and switching energies.

In Chapter 5, graphene is introduced as a potential active plasmonic material, which shows large tunability of its permittivity-function as well as extreme surface plasmon confinement unprecedented in noble metals. The optical properties of graphene are analyzed, which depend on its operating frequency, chemical potential and finite widths. Figure-of-merit (FoM) formulae are then developed to characterize the waveguide performance of graphene nanoribbons (GNRs). Based on the FoMs, a GNR waveguide plasmonic modulator is designed. The GNR waveguide plasmonic modulator is implemented into the active GNR active power splitter, which has structure based on a cross-junction waveguide. The active splitting performance is optimized through the use of plasmonic stubs. The GNR active power splitter is further scaled up into large arrays of active waveguide networks. Fabrication steps of the GNR active waveguide networks are also proposed, which is largely CMOS compatible and easy to be implemented in massive scale.

Finally, in Chapter 6, a summary of the research milestones is given, and the direction of future works is proposed. A variety of research areas such as nonreciprocal magnetoplasmonic waveguides and strained-induced nonlinear materials are among the subjects of interest for future consideration.

Chapter 2

A Monopole Antenna-assisted Waveguide-coupled Cavity Plasmonic Detector

In this chapter, we first give a brief overview of the traditional photonic photodetector to examine its shortcomings and hence the motivation to develop the plasmonic detector. Following this, we explore the state-of-the-art plasmonic detector designs to get a better understanding of the challenges faced in this area of research. From here, we investigate the possible areas of the plasmonic detector design to improve on and then propose a novel plasmonic detector based on the monopole antenna-assisted resonant detector cavity design. We lay out the design principles for the resonant monopole antenna and resonant detector cavity, which is confirmed using simulation studies. Our optimized structure for the detector design yields a 42% optical power absorption. We compare our design to that of a dipole antenna detector, and find that our design has higher optical power absorption, a more compact and integrated structure, and an easier fabrication process.

2.1 An overview of photonic photodetectors

The waveguide integrated germanium photonic detector has been around for quite some time, but it is within the past few years that the photonic detector underwent some tremendous improvements in responsivity, quantum efficiency and operating bandwidth. It is well known that silicon technology is unable to produce high efficiency detectors due to the wide bandgap of silicon that is incompatible with the near-infrared operating wavelength. However, the improvements in growth techniques of germanium crystals on silicon heralded the start of a new research area of high

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efficiency chip-scale integrated germanium photodetectors [19]. Germanium is a highly absorptive material that can convert light into electron-hole pairs and subsequently transform them into electricity.

The performance of germanium on silicon photodetectors developed in the recent years has been largely optimistic. Record responsivity values of over 1A/W have been achieved, while bandwidths are reported to be as over 120 GHz [20–22]. However, the primary drawback of the germanium photodetector is its large size. All germanium photodetectors mentioned above have cross-sections of at least a few square-micrometers, and absorption lengths of tens of micrometers. This large device footprint greatly affects the scalability of chip integration, especially when it comes to very-large-scale integration (VLSI) and ultra-large-scale integration (ULSI) implementations.

Hence, this research aims to develop plasmonic photodetectors that scale below the diffraction limit. We will first take a look at a few state-of-the-art plasmonic detectors to identify the areas to improve on.

2.2 Plasmonic detectors: state-of-the-art

Here we examine 4 case studies of devices designed in the recent years (from 2008–2010) [23–26], depicted in Figure 2.1. All detector structures presented in these cases are constructed using a metal–semiconductor–metal (MSM) absorption cavity design, which has a potential intrinsic detection bandwidth of THz range for nanometer-scale semiconductor gap widths [27]. For the structure in Figure 2.1(a), optical detection is done for plasmonic waves directly coupled into the gap region, while for structures in Figure 2.1(b)–(d), coupling of surface plasmons is assisted by the use of optical

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nanoantennas. It should be noted that for the plasmonic detector in Figure 2.1(a), the active material absorption length is as thick as $1\mu\text{m}$, while for the plasmonic detectors in Figure 2.1(b)–(d), their active material lengths do not exceed 200nm . Thus it can be seen that nanoantennas play an important role in improving coupling efficiencies and strongly confine light in subwavelength volumes.

Figure 2.1: Metal-semiconductor-metal (MSM) plasmonic detectors. (a) Gap plasmon detector [23]. (b) Open-sleeve dipole [24]. (c) Waveguide-coupled dipole [25]. (d) Waveguide-coupled L-shaped dipole [26].

Waveguide-coupled detectors rely on dipole antennas – for example, a straight-rod dipole [25] or L-shaped dipole [26] – for efficient surface plasmon coupling. The straight-rod dipole antenna can efficiently couple surface plasmons into the detector cavity. However, it cannot effectively localize the surface plasmons, because the dipole feedgap is not designed as an optical resonator. As such, optical power absorption is low. The L-shaped dipole antenna, meanwhile, extends the dipoles perpendicularly with nanorods along the feedgap. The extension forms the

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required cavity length to support resonant cavity modes. Consequently, there is a 4-times increase of optical power absorption. This shows that the resonance of both the antenna and detector cavity are important for efficient reception and confinement of the surface plasmons.

The detectors in the previous designs are separated from the MIM waveguide by a coupling-gap [25, 26]. This is required in order to form the dipole antenna arms. However, the gap also causes optical power leakage, thus reducing the coupling efficiency. Furthermore, in device fabrication, the gap size (usually from 20–50nm) and position are difficult to achieve accurately in conventional CMOS process. Thus removing the gap in between the waveguide and the detector might be vital to increase the coupling efficiency of the antenna.

So far we have seen plasmonic detectors designed for coupling with MIM waveguides. However, the discovery and invention of hybrid plasmonic waveguides have offered innovation possibilities [14]. In this research, we propose to integrate a monopole antenna onto the hybrid plasmonic waveguide to obtain an entirely new plasmonic detector design. This type of antenna does not require a coupling-gap separation from the waveguide, as will be shown in the design below.

2.3 Principles of the monopole antenna-assisted plasmonic detector design

The hybrid plasmonic waveguide shown in Figure 2.2(a) consists of a low-index dielectric layer sandwiched in between a metal layer and a high-index dielectric layer. In contrast to the MIM plasmonic waveguide, the hybrid waveguide structure allows the placement of a monopole antenna as shown in Figure 2.2(b). We can view the metal part of a long waveguide as an infinitely-large conducting ground plane. We

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can then make an indentation and insert a metal nanorod through the dielectrics, forming a simple monopole antenna. The antenna is separated from the ground plane by a feed-gap, where the optical power is supposed to be localized. As the reception of a monopole antenna is omnidirectional, we can still make use of the hybrid plasmonic waveguide to directly feed surface plasmons into the gap for optical detection.

Figure 2.2: (a) A hybrid plasmonic waveguide stack consists of a metal layer, a low-index and high index dielectric layers. (b) A monopole antenna is attached to a hybrid plasmonic waveguide, separated by a feed.

Figure 2.3: The monopole antenna-assisted detector cavity is directly integrated with the hybrid plasmonic waveguide.

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The amount of optical power which can be directly coupled into the detector cavity depends on how the antenna and detector cavity are designed. The antenna has a frequency-dependent resonance length that allows efficient coupling of the surface plasmons, while the detector cavity has to be structured as an optical resonator to confine the surface plasmons for absorption inside the detector cavity.

2.3.1 Monopole antenna design

The monopole antenna is essentially a half dipole antenna: one of the dipole antenna arms is replaced with a large conducting ground plane. The electromagnetic waves that are reflected from the large ground plane complete the radiation pattern of the missing antenna arm. Since the metal layer of the hybrid plasmonic waveguide serves as the conducting ground as previously depicted in Figure 2.2(b), we can thus attach the detector right at the waveguide terminal as shown in Figure 2.3, using a direct waveguide–detector butt-coupling scheme.

A resonant optical antenna has the ability to either receive or transmit electromagnetic waves at maximum efficiency. The resonance arises from the impedance-matching of electromagnetic wavelengths to antennas: dipoles have resonance lengths of $L_r = n(\lambda/2)$ and monopoles have resonance lengths of $L_r = n(\lambda/4)$ [28]. However, the resonance lengths for optical antennas are observed to be shorter than radio-frequency antennas. For example, in ref. [29], an 80nm aluminium monopole has a resonance wavelength of 514nm, while in ref. [30], the a 250nm gold dipole is resonant to a wavelength of 830nm.

There are two factors contributing to the shortened optical antenna resonance lengths. The first effect comes from the finite permittivity of metals at optical

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frequencies. The effective wavelength λ_{eff} for a metal-dielectric interface can be written as:

$$\lambda_{eff} = \left(\frac{\epsilon_s + \epsilon_m}{\epsilon_s \epsilon_m} \right)^{1/2} \lambda \quad (2.1)$$

where ϵ_s is the dielectric permittivity and ϵ_m is the metal permittivity. ϵ_m is effectively infinite at radio frequencies, but drops to the order of $10-10^3$ at optical frequencies. ϵ_s is relatively unchanged for all frequencies. Thus, when ϵ_m is finite, the effective wavelength is shorter and has greater dependency on ϵ_m .

The second effect comes from the finite shape of the antenna at nanoscale. At the optical regime, the magnitude of the skin depth is in the same order of the dimensions of antenna elements [31]. For a rod-shaped antenna, λ_{eff} is given by [31]:

$$\lambda_{eff} = \frac{\lambda}{\sqrt{\epsilon_s}} \sqrt{\frac{x}{1+x}} - \frac{4r}{N} \quad (2.2a)$$

and

$$x = 4\pi^2 \epsilon_s \left(\frac{r^2}{\lambda^2} \right) \left[\frac{13.74 - 0.12 \left(\frac{\epsilon_\infty + 141.04 \epsilon_s}{\epsilon_s} \right)}{+ 0.12 \left(\frac{\sqrt{\epsilon_\infty + 141.04 \epsilon_s}}{\epsilon_s} \right) \frac{\lambda}{\lambda_p}} \right]^2 \quad (2.2b)$$

where r is the rod radius, λ_p is the plasma wavelength, N is the resonance order, and ϵ_∞ is the dielectric function of metal at the infinite frequency limit. In Eqn. (2.2a), the first term on the right displays the effect of finite antenna radius. The second term $4r/N$ comes from the rod-end reactance. Higher order resonances are supported in longer rod lengths, but they will be longer than integer-multiples of the first λ_{eff} due to the scaling factor of N .

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Farfield antennas couple electromagnetic waves by electromagnetically exciting electrical currents on the antenna element and then delivering them to the feed. For a waveguide-coupled photodetector, however, the surface plasmons has to be delivered directly into the detector cavity for absorption in order to generate electron-hole pairs. Thus, as an additional design caveat, there is a need for maximum current distribution at the base of the monopole where the detector cavity is located. It turns out that only odd order standing waves have this property, as shown in Figure 2.4(b) and (d) [28]. The current distribution of even order standing waves, meanwhile, is maximum on the antenna arm as shown in Figure 2.4(c). The surface plasmons on the antenna arms would thus be heavily absorbed by the antenna before reaching the detector cavity.

Figure 2.4: Antenna current distribution profiles for (a) $l \ll \lambda$, (b) $l = \lambda/2$, (c) $\lambda/2 < l < \lambda$ and (d) $\lambda < l < 3\lambda/2$. Adapted from Balanis (2005) [28].

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2.3.2 Resonant detector cavity design

Apart from efficient coupling, the optical power must also be confined in the detector cavity for maximum absorption to occur. Efficient confinement requires an optical resonator to provide positive optical feedback. This is achieved when the detector cavity supports standing waves, for example, using a Fabry-Pérot cavity. The fundamental mode is a half-wavelength, depending on the geometry and dielectric permittivity of the detector cavity.

2.4 Simulation methodology and data interpretation.

Figure 2.5: Input and output Poynting vectors (red arrows) from the detector active volume (green block).

For the cavity detector, our primary interest is to know the optical power which is retained/localized inside the detector active region. As such, we probe the optical power Poynting vector of the six surface areas of the active volume, as shown in Figure 2.5. Optical power travelling in the $+x$ direction into the active volume is from the input waveguide. Optical power travelling out from the active volume in the $+x$ and $\pm z$ directions is the leakage optical power. Optical power travelling out from the

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active volume in the $\pm y$ directions is the metal damping, since the $\pm y$ faces are directly interfaced with the metal. All these optical power losses from the active volume should be subtracted from the input optical power to get the residual power which stays inside the detector.

Figure 2.6: Optical power from a reference hybrid plasmonic waveguide.

To get the percentage power which is absorbed by the detector, we must first define the input optical power. Here, we cannot directly retrieve the input optical power from the optical power travelling in the $+x$ direction into the active volume shown in Figure 2.5. This is because any changes to the detector structure will change its impedance, and consequently change the in-coupling optical power. As such, we need to obtain the optical power input from a reference hybrid plasmonic waveguide, as shown in Figure 2.6. By simulation of a reference 1000nm-long hybrid plasmonic waveguide, we can obtain its output optical power, to be used as the reference input optical power for the detector. Hence, the input optical power can be fixed at the reference value, making comparisons of absorption efficiency more convenient. Finally, the residual power which stays inside the active volume can be divided by the reference input optical power to get the percentage absorption power, i.e. the absorption efficiency.

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2.5 Simulation results and discussion

In our simulations, the hybrid plasmonic waveguide is formed by a stack of aluminium, 150nm silica and 150nm silicon layers. This waveguide dimension has been optimized for best confinement and propagation distances. Germanium absorption material is located at the antenna feed. The device is 220nm in height, planarized, and operates at 1.55 μ m wavelength. Material parameters (ϵ (aluminium) = $-252.5+46.07i$, $\lambda_p = 96.7$ nm and $\epsilon_\infty = 1$; ϵ (silica) = 2.085; ϵ (silicon) = 12.11; ϵ (germanium) = $18.28+0.0485i$) are taken from ref. [32].

Figure 2.7(a) shows that a resonant antenna enhances the optical power absorption in the detector cavity. The power absorption enhancement factor is defined as the power absorption efficiency of the monopole antenna-assisted cavity detector over that of a detector without an antenna, as shown in the schematic in Figure 2.7(c). The antennas are resonant at 150nm, 350nm and 600nm lengths, much shorter than the free space wavelengths. Moreover, high order resonances are longer than multiples of the first resonance length L_{fr} . For example, the second order resonance is longer than $2 \times L_{fr}$ at 350nm, and the third order resonance is longer than $3 \times L_{fr}$ at 600nm.

To confirm simulation results with theory, we can numerically estimate the lengths using Eqn. (2.2). If we approximate the antenna radius to be ~ 100 nm, the first resonance length is estimated to be 167.3nm. The slight discrepancy comes from the complicated antenna system, noting that the antenna in the simulation interfaces with several different background materials. The inhomogeneous background dielectric permittivity also affects the higher order resonance lengths. As an example, the

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150nm antenna has germanium, silica and silicon background material in proportion, but the 600nm antenna has mainly silica as background material.

Figure 2.7: (a) Optical power absorption as a function of antenna length. Inset: 1-D antenna current distributions. (b) 2-D antenna current distribution map. (c) Schematic of the detector cavity without an antenna.

It is seen from the inset in Figure 2.7(a, ii) that the 350nm antenna has a minimum current distribution at the base of the antenna. Meanwhile, the 2-D antenna current maps in Figure 2.7(b) show that a significant amount of current is being distributed along the arm of the 350nm antenna (white arrow). This confirms that

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optical power is not efficiently coupled to the feed for even order resonances, and thus we must only employ odd order resonances in our detector design. As seen from Figure 2.7(a), the presence of odd order resonant monopole antennas provides up to 12-times increase in optical power absorption for the detector cavity.

Figure 2.8: (a) Optical power absorption as a function of detector cavity length. (b) Optical power absorption as a function of both detector cavity length and width. Electric-fields maps for (c) a 150nm–long detector cavity and (d) a 300nm–long detector cavity.

Efficient localization of optical power is achieved using a resonant detector cavity. Figure 2.8(a) shows that optical power absorption peaks when the detector cavity supports resonant cavity modes. The 150nm–long cavity in Figure 2.8(c)

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supports a half-wavelength standing wave, while the 300nm-long cavity in Figure 2.8(d) supports a full-wavelength standing wave. The 300nm-long cavity has a longer absorption volume, thus it has a higher absorption of optical power compared to the 150nm-long cavity. However, longer cavities increase the device footprint, and might potentially increase device capacitance as well.

To obtain a high electric-field intensity and optical confinement, the cavity width should be as small as possible. However, a small cavity width also translates to a small light-matter interaction volume, decreasing the absorption cross-section. Balancing between the two factors, there is an optimal cavity width for maximum optical localization and absorption. The highest optical power absorption occurs at a 60nm cavity width, shown in the contour plot of Figure 2.8(b).

Figure 2.9: Optical power distribution for detector cavities with (a) waveguide-integrated monopole antenna and (b) gap-separated dipole antenna.

Overall, it is shown that a 150nm×60nm detector cavity length × width and a 600nm-long antenna give the most efficient plasmonic detector, achieving 42% optical power absorption. In comparison, the straight-rod dipole antenna detector

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(scaled to similar dimensions) only achieved 27% optical power absorption [25]. The reduced optical power absorption originated from the formation of an MIM gap in between the metal waveguide layer and one of the antenna arms. A portion of surface plasmons will travel in this MIM gap, as shown in Figure 2.9(b) (white arrow). Surface plasmons in this gap are damped out before being returned to the detector cavity. In contrast, this gap leakage is not present in the monopole detector as shown in Figure 2.9(a).

2.6 Discussions on device implementation

To use the designed structure as a plasmonic detector, it is required to apply a bias voltage across the germanium absorption cavity. Electrodes can be connected from the antenna and the aluminium ground to the external circuitry since they are already in contact with the detector cavity. To avoid affecting the antenna resonance, the electrode connecting from the antenna arm should be in perpendicular. On the other hand, the electrode connecting from the aluminium can extend below the ground plane to minimize additional resonance effects. One suggested placement of aluminium electrodes (cross-section $150\text{nm} \times 220\text{nm}$) is shown in Figure 2.10. From simulation, there is only a 2% optical power absorption loss using this arrangement. Using metal electrodes is a huge improvement from using transparent conducting oxide (TCO) electrodes, as the latter has high resistance and potentially increases the required bias voltage. On the other hand, TCO electrodes are required when connecting to dipole antennas to avoid affecting the antenna resonance [26].

Compared to the dipole antenna detector, the waveguide-coupled monopole antenna-assisted cavity detector is gapless and thus easier to fabricate. There will be minimal alignment issues because the waveguide and detector are integrated.

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Lithographic mask sets would be made simpler in the absence of the gap and one antenna arm. In addition, since the electrodes are also made of metal, the TCO deposition step is not required. All fabrication steps and materials are compatible to the CMOS process.

Figure 2.10: Arrangement of electrodes attached to the plasmonic detector.

2.7 Detector speed, responsivity and spectral bandwidth

The resonant nanocavity detector would be expected to operate at high speeds due to its small electrode spacing. First we will estimate its intrinsic speed, given by the time needed for the electron-hole pairs inside the germanium to travel to the electrodes. We assume that germanium is hole mobility-limited at $\mu_h \sim 2000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. Then, assuming we have a $V = 0.01 \text{ V}$ bias, and an average electron/hole transit distance of $L = 30 \text{ nm}$ across the electrode spacing of $d = 60 \text{ nm}$, the transit time is given by:

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$$t = \frac{Ld}{\mu_h V} = 900 \text{ fs} \quad (2.3)$$

which translates to an intrinsic speed of $\sim 1\text{THz}$.

The responsivity, meanwhile, is given by:

$$R = \eta \frac{\lambda(\mu m)}{1.23985} = 0.6 \quad (2.4)$$

if we assume the quantum efficiency, η to be 50%.

Figure 2.11: 3dB FWHM spectral bandwidth of the plasmonic detector

Shown in Figure 2.11 is the 3dB spectral bandwidth of the plasmonic detector, which is about 31THz. The high spectral bandwidth compared to resonant-cavity-enhanced (RCE) photodetectors [33] is expected as the cavity is of low Q-factor due to the losses from the metal. The spectral bandwidth is high enough to meet the current channel bandwidth requirements of $> 100\text{Gbit/s}$.

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2.8 Conclusions

We have proposed a monopole antenna-assisted waveguide-coupled detector cavity for efficient coupling and absorption of optical power. The monopole antenna is mounted onto the metal layer of the hybrid plasmonic waveguide end, and is separated by a feed-gap which forms the detector cavity. Optical power absorption of 42% in a $220 \times 150 \times 60 \text{ nm}^3$ germanium cavity is achieved with enhanced optical coupling using a 600nm-long resonant monopole antenna and optical power localization using a 150nm-long resonant detector cavity. The proposed monopole antenna detector is a great improvement from dipole antenna detectors, showing increased optical power absorption, a more compact and integrated detector-waveguide structure, the use of metal electrodes, as well as easy fabrication steps.

Chapter 3

Enhanced Plasmonic Detectors using Plasmonic Coupled-cavities

In this chapter, we analyze the underperforming areas of the monopole antenna-assisted cavity detector to find aspects for improvement. We find that the optical power localization is not optimized due to the inefficient cavity resonator structure, which only depended on Fresnel reflections to provide for the optical feedback. As such, we take cues from the cavity-coupling techniques to install additional coupler and reflector cavity components to the plasmonic detector. The quarter-wave coupler improves surface plasmon coupling, while the reflector attenuates surface plasmon leakage from the detector cavity. We find that the strongly-coupled cavities tremendously increase the surface plasmon localization inside the detector cavity, bringing up the detector cavity's optical power absorption to 78%.

3.1 Improvement of optical power absorption of the plasmonic detector by using coupler and reflector cavities

In [Chapter 2](#), we have designed a plasmonic detector that can absorb as much as 42% of optical power that is coupled from a hybrid plasmonic waveguide. While this figure is decent, much can still be done to improve the performance of this detector.

One of the shortcomings of this detector design is that the optical power localization efficiency of the detector cavity is dependent on Fresnel reflections to provide for the optical feedback. The Fresnel reflections are in turn completely dependent on the interfacing materials' refractive indices, which in this case are germanium (Ge, $n = 4.28$) and silicon dioxide (SiO_2 , $n = 1.44$). Fresnel reflections are

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highly imperfect reflections: a Ge-SiO₂ interface only provides a reflectance of 24.7%. As such, some of the surface plasmons would leak out from the cavity-end. In our simulation studies, it is found that as high as 33.5% of the optical power coupled into the detector cavity leaks into the background material (as shown in the poynting-vector diagram in Figure 3.1). This amount is considerably large and cannot be overlooked.

Figure 3.1: Optical power leakage from the germanium detector cavity due to imperfect Fresnel reflections. The arrows represent the poynting-vectors of optical power flow.

The usual way of preventing optical power leakage from cavities is through the use of a dielectric mirror [34]. The dielectric mirror consist of multiple optical thin film layers, stacked together to create high reflectivity. However, since our detector structure is a nanoscale waveguide, thin film deposition poses a high technical challenge. An alternative is the Bragg reflector grating, which may be suitable for waveguides and can be realized by lithography [35]. However, the grating is usually physically long, which is undesirable for nanoscale implementations.

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Instead, we can consider metal reflectors for subwavelength nanocavities. Previously, the use of metal reflectors in optical cavities is generally avoided due to their high optical losses, especially when constructing high Q-factor resonators. However, in our case, it would be used for an absorption cavity, and thus the metal optical losses are less of a concern. Moreover, since metals are already present in our plasmonic structure, the addition of metal components is streamlined in the fabrication process. On top of that, it would be sufficient to make a thin metal reflector to achieve high reflectivity since electric-fields cannot penetrate metals thicker than their skin depths ($\sim 20\text{nm}$).

Figure 3.2: A reflector component added at the end of the detector cavity to reduce optical power leakage.

We have proposed to add a reflector component at the back of the detector, as shown in Figure 3.2, to reduce the optical power leakage from the detector cavity. The placement of the reflector forms another cavity directly adjacent to the detector cavity, which allows space for the leaked surface plasmons to oscillate and be reflected back. The size of the reflector cavity can be adjusted for perfect phase-

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matching to obtain maximum reflection. Simulation of this structure shows that an optimized reflector component raises the optical power absorption of the detector cavity from 42% to 55%. The improved difference, however, is only 13%, which does not fully correspond to the 33.5% optical power leakage. The reason is because even though the surface plasmons are reflected back into the detector cavity from one end, reflection at the front end has increased as well, preventing efficient coupling of surface plasmons into the detector cavity.

Figure 3.3: A quarter-wave coupler added in between the hybrid plasmonic waveguide and the detector cavity to increase optical power coupling.

This leads us to the design of another component which is ubiquitous in the field of radio transmission: the quarter-wave impedance transformer [36]. The quarter-wave impedance transformer is an element which transforms the load impedance (i.e. the detector cavity) to match the input impedance (i.e. the hybrid plasmonic waveguide). Thus, maximum optical power can be coupled from the hybrid plasmonic waveguide to the detector under a perfect-matching condition, achieved by using a quarter-wave coupler. As shown in Figure 3.3, the coupler is just a short MIM cavity that sits in between the hybrid plasmonic waveguide and the detector cavity.

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Simulation of this structure shows that an optimized MIM coupler improves the optical power absorption from 42% to 50%. This gives another 8% improvement of optical power absorption in addition to the 13% from the reflector cavity.

From these independent simulation results, in total we would be expecting a 21% increase in optical power absorption when combining the contributions from the reflector and coupler components. However, when we simulated the combined structure, we found that the optical power absorption increased to 78%! This is an improved difference of 36%, beyond our expectations. It is observed that this improved performance comes from increased cavity resonance optical power localization inside the detector cavity. We attribute this exceptional performance to the cavity-coupling phenomenon.

3.2 Cavity-coupling to enhance transmission, reflection or localization

The concept of cavity-coupling has long been present in electronics, for example, in coupled-cavity travelling-wave tubes (CCTWT) [37]. Cavity-coupling is a resonant technique which can tailor either pass-bands (high transmission) or stop-bands (high reflection) for electromagnetic waves with the careful adjustment of the individual cavity sizes and separation gaps. In effect, this can also “slow down” the electromagnetic waves by slowing down the group velocity [38], or even stopping them altogether, achieving localization.

In photonics, cavity-coupling techniques are used in photonic crystals [39, 40]. Light can be slowed down by as high as two orders in such photonic crystal waveguides, and this contributes to a higher light-matter interaction lifetime. Therefore, photonic crystals are often used in combination with nonlinear materials to

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enhance the nonlinear effects, thereby reducing device lengths and drive-energies [41]. Recently, cavity-coupling techniques are also adapted into plasmonics crystals as well. For example, surface plasmons are shown to be able to tunnel through resonant plasmonic cavities separated by gaps [42]. Tuning the coupling coefficients of these plasmonic cavities also enables one to tune to group velocity of the surface plasmons, thereby slowing the surface plasmon propagation [43].

Figure 3.4: A coupled-cavity system design comprising coupler, detector and reflector cavities arranged in series.

We have drawn inspiration from the concept of cavity-coupling to design a coupled-cavity system for our plasmonic detector, as shown in Figure 3.4. The system comprises of coupler, detector and reflector cavities arranged in series. By tuning the resonances of both the coupler and reflector cavities, strong surface plasmon localization inside the detector cavity can be achieved. In the next few sections we will analyze in detail the parameters that affect the respective cavity resonances.

3.2.1 Coupler cavity

The coupling of surface plasmons into the detector cavity is enhanced by the coupler cavity. Maximum coupling is achieved through perfect impedance-matching. The

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relationship of the input impedance Z_{in} (i.e. the hybrid plasmonic waveguide), the coupler impedance Z_0 , and the load impedance Z_L (i.e. the detector and reflector cavities) is given as:

$$Z_{in} = Z_0 \frac{Z_L + iZ_0 \tan(\beta l)}{Z_0 + iZ_L \tan(\beta l)} \quad (3.1)$$

where i is the imaginary unit, $\beta = 2\pi/\lambda$ is the wave vector and l is the coupler length. An interesting case is seen when l is designed as odd multiples of $\lambda/4$: $\tan(\beta l)$ will tend towards infinite, reducing the equation to the dual of impedances:

$$\frac{Z_{in}}{Z_0} = \frac{Z_0}{Z_L} \quad (3.2)$$

Thus, maximum coupling is achieved using a quarter-wave coupler. Further optimization on the impedance-matching can be made by tuning the coupler impedance to:

$$Z_0 = \sqrt{Z_{in} Z_L} \quad (3.3)$$

The coupler impedance can be tuned by selection of its cavity constituent materials and also by adjusting the cavity width.

Similar to optical antennas, the effective lengths of the quarter-wave coupler needs to be scaled using optical-regime scaling laws [31]. As previously shown in Eqn. (2.2a), the effective wavelengths will be very much shorter than free-space wavelengths, and higher order resonances will be longer than integer-multiples of the first effective length (refer to [Chapter 2](#), subsection [2.3.1](#)).

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3.2.2 Reflector cavity

The reflector cavity reflects the surface plasmons that are transmitted from the detector cavity, thereby suppressing the surface plasmon leakage. A good reflector cavity should prohibit any positive optical feedback inside itself to prevent optical power localization in the wrong cavity. Therefore, the design of the reflector cavity has to be off-resonant through destructive interference. The condition for destructive interference inside the cavity is fulfilled when:

$$2d\beta + \Delta\phi = (2n-1)\pi, \quad n = 1, 2, 3, \dots \quad (3.4)$$

where d is the cavity length, β is the wave vector, and $\Delta\phi$ the relative phase-shift on reflection between two reflective interfaces. The phase-shift on reflection of an interface can be calculated by the following equation:

$$\phi(r) = \tan^{-1} \frac{\text{Im}(r)}{\text{Re}(r)} = \tan^{-1} \frac{2n_s k}{n_s^2 - n^2 - k^2} \quad (3.5)$$

where n_s is the refractive index of the cavity material, and $n+ik$ is the refractive index of the germanium and aluminium surfaces. Using material parameters from ref. [32]: n_s (silica) = 1.44, $n+ik$ (germanium) = 4.276+0.0242i and $n+ik$ (aluminium) = 1.44+16i, ϕ is calculated to be 0.998π for germanium and 0.943π for aluminium. This gives a $\Delta\phi$ of 0.055π . Using this value in Eqn. (3.4), d can be estimated to be 254nm.

3.2.3 Detector cavity

The detector cavity retains its optimized parameters as laid out in [Chapter 2](#). Though optical coupling is assisted by the coupler cavity, the antenna remains an essential element to ensure maximum optical power is distributed at the antenna feed.

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Likewise, the dimension of the detector cavity has to be resonant to ensure the build-up of optical power stays localized inside the cavity.

3.3 Simulation results and discussion

The optical power absorption of a detector cavity depends on the presence or absence of a coupler and reflector as shown in Figure 3.5(a). Case (i) refers to the lone detector cavity which has optical power absorption of 42%. Adding the resonant coupler alone in (ii) increases the optical power absorption by 8%, while adding the optimized reflector alone in (iii) increases it by 13%. Adding both components in (iv), however, increases the optical power absorption by 36%. In the same Figure 3.5(a), we also observed the resonant coupler lengths to be at 150nm and 650nm, consistent with the wavelength scaling rules in the optical regime. The longer resonant coupler (650nm) has a slightly reduced optical coupling due to the increased metal losses.

Figure 3.5: (a) Optical power absorption of the detector cavity as a function of coupler length for cases (i) without a coupler or reflector, (ii) with a coupler but without a reflector, (iii) without a coupler but with a reflector, and (iv) with a coupler and reflector. (b) Optical coupling efficiency as a function of coupler width.

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As mentioned before, the efficiency of the coupler cavity also depends on its optimized impedance. This depends on the effective refractive index of the coupler cavity, which is dependent on its width and dielectric material refractive index. In this case, we constrain our discussion to only the optimization of the coupler-cavity width, as we would prefer to keep the dielectric material as silica for streamlined fabrication. Shown in Figure 3.5(b) is the optical coupling efficiency as a function of the coupler width. Optical coupling is low for narrow widths, and relatively constant for widths greater than 140nm. It is thus sensible to streamline the coupler width to the hybrid plasmonic waveguide insulator width, which is taken to be 150nm.

Figure 3.6: (a) Optical power localization as a function of the reflector cavity length and width. (b) Optical loss mechanisms from the reflector cavity.

Next, we investigated the effect of reflector cavity dimensions on the optical localization efficiency. It is shown in Figure 3.6(a) that the maximum reflection occurs at cavity lengths of 250nm and 800nm, in line with the theoretical predictions. Meanwhile, the reflection degrades if the cavity width is not within the range of 200nm–700nm.

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In Figure 3.6(b) we show that the losses of the reflector cavity occur through two main mechanisms: the damping loss, when the surface plasmons are lost by metal absorption in the $+x$ and $\pm y$ directions, and the radiative loss, when the surface plasmons are lost in the $\pm z$ directions into the background. The values of these losses can be easily obtained from the simulation results by applying the data interpretation method as mentioned in Chapter 2. When the cavity width is small, the field confinement inside the cavity is stronger and thus the damping loss is high, as shown by the higher tail-front of the damping loss curve in Figure 3.6(b). When the cavity width is big, damping loss is seen to be lower. The main optical loss mechanism, however, is through radiation as shown by the high tail-end of the radiative loss curve in Figure 3.6(b). This indicates that the cavity width affects the transverse surface plasmon mode-matching of the reflecting surfaces, a property also seen in photonic-plasmonic waveguide couplers [44].

Figure 3.7: Optical in-coupling and out-coupling efficiencies are dependent on the presence and absence on the coupler and reflector.

Finally, to examine the cavity-coupling phenomenon in more details, we look at the in-coupling (coupling from the coupler cavity into the detector cavity) and out-

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coupling (coupling from the detector cavity into the reflector cavity) efficiencies in Figure 3.7. The role of the reflector is straight-forwardly shown, whereby its presence significantly reduces the out-coupling efficiency. Meanwhile, the in-coupling efficiency shows a more interesting relation. With reflectors, the optical in-coupling shows enhanced peaks using quarter-wave couplers, and sunken troughs using half-wave couplers, compared to the cases without reflectors. All these result in the increase of total optical power localization.

Figure 3.8: Schematic on the effect of round trip increase inside the detector cavity due to the presence of coupled cavities.

We believe that the increase in optical power localization comes from the increased longitudinal cavity resonance provided by the coupled-cavities. When the surface plasmons enter the detector cavity, they are able to make more round trips inside the active volume (shown in the schematic in Figure 3.8) because the transmission efficiencies at the interfaces (seen from inside the detector cavity) are reduced. This results in a larger constructive interference inside the detector cavity, and also a larger destructive interference inside both adjacent cavities. As a result, the

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surface plasmons inside the detector cavity experience a stronger resonance and thus an increased longitudinal cavity confinement. We have also shown the mathematical proof of this phenomenon in [Appendix A](#).

Finally, bias electrodes will be needed for real circuit applications. As such, a thin slit has to be cut through the reflector (indicated in [Figure 3.4](#)) in order to electrically isolate the contacts of the detector cavity. Our simulation results show that the effect of the isolation layer on the metal reflectance is insignificant for isolation widths within 300nm. In this case, the reflectors can also be used as the electrodes as they are electrically-connected to the detector cavity.

3.4 Detector speed and spectral bandwidth

The intrinsic detector speed is similar to that of the single cavity detector in [Chapter 2](#).

Figure 3.9: 3dB FWHM spectral bandwidth of the coupled cavities detector.

Meanwhile, we obtain the 3dB spectral bandwidth as shown in the graph in [Figure 3.9](#). It has a 3dB bandwidth of around 31THz.

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3.5 Conclusions

We have analyzed and determined that the surface plasmon leakage is the cause for reduced performance of the monopole antenna-assisted plasmonic detector. Henceforth, we proposed a coupled-cavity system to enhance the surface plasmon localization inside the plasmonic detector. The plasmonic coupled-cavity system is a series of coupler, detector and reflector cavities placed adjacent to each other. Our investigations show that the cavity-coupling phenomenon synergizes the coupling between all three cavities, enhancing the resonance and optical power localization inside the detector cavity. In total, the coupled-cavity system boosts the optical power absorption of the plasmonic detector from 42% to 78%.

Chapter 4

Vanadium Dioxide Dual-mode Plasmonic Waveguide Modulator

In this chapter, we first review the current status of plasmonic modulators to determine the aspects in need of improvements. We then propose to use vanadium dioxide (VO_2) as the active material for plasmonic modulators, owing to its high refractive index switching contrast and ultrafast switching speed. We apply VO_2 in various modulator designs, for example, in waveguide and ring modulators. The focus of this chapter would be the design of a novel VO_2 dual-mode plasmonic waveguide electroabsorption modulator that promises high modulation depths, low insertion losses, and low energy-consumption in ultrashort device lengths. We found that the remarkable efficiency of this novel modulator comes from its ability to perform mode-switching between low-loss hybrid plasmonic modes and high-loss MIM modes, on top of having a high extinction coefficient switching contrast.

4.1 Review of plasmonic modulators

The research field of plasmonics has always been active in the progress of plasmonic modulators. The review paper by MacDonald and Zheludev provides us with a good summary and outlook on the future of plasmonic modulators [16]. Alternative switchable media alongside with efficient modulator structure designs have to be considered as we continue to push the performance of plasmonic modulators towards 100Gb/s bandwidths, attojoule per bit switching energies, and nanoscale device footprints.

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All classic optoelectronic modulators use either one of these modulating schemes: refractive index or extinction coefficient modulation. The type of modulator structure will depend on which scheme is chosen. From the refractive index modulation approach, the goal is to modulate the light distribution inside the media, which then results in the modulation of the output intensity. Types of modulators that use this scheme include the interferometers [45, 46], channel switchers [47], and resonators [48]. On the other hand, from the extinction coefficient modulation approach, the light absorption efficiency of the switching medium is modulated to control the output intensity. Most modulators which use this scheme are waveguide electroabsorption modulators [49, 50].

A good modulator structure design can help to reduce insertion losses and driving powers. However, the modulation depth, size and energy-consumption of the device still depend very much on the nonlinear coefficient of the active material. For example, the thermo-optical nonlinear polymer has a low thermo-optical coefficient of $2.53 \times 10^{-5} \text{ K}^{-1}$, thus requiring a long active waveguide length of 5.7mm [45]. Silicon has a refractive index change of only $\Delta n = 10^{-3}$ [51], while barium titanate is higher by an order at $\Delta n = 0.05$ [52].

Recent progress in material science and engineering has led to the discovery of various new nonlinear materials. For example, the enhancement of nonlinearity by symmetry-breaking of crystals has been discovered in strained-silicon [53], which induced a 15pm/V electro-optic coefficient in silicon. Giant modulation has also been reported in organic polymers, which is often used in conjunction with silicon to build hybrid organic–silicon devices [54]. It is also discovered that aluminium metal can be an active medium under intense optical excitation [55]. Unity-order refractive index

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change is reported in indium tin oxide (ITO) [56], which led to the design of ultracompact modulators [50, 56]. The refractive index change of ITO only occurs near the surface of the material due to the Thomas-Fermi screening effect. Recently, doped graphene is discovered as an excellent active plasmonic material with huge control of its permittivity-function [57], which we will explore in more details in Chapter 5.

In this chapter, we will explore phase-change materials as the active switching media. In particular, we are interested in vanadium dioxide (VO_2), a Mott insulator which also shows unity-order refractive index change throughout the bulk material [58]. This makes VO_2 a potentially efficient and highly configurable nonlinear material that can be used in the design of high performance plasmonic modulators.

4.2 Properties of vanadium dioxide (VO_2)

VO_2 is a Mott insulator which shows a first-order insulator-to-metal transition (IMT) under a variety of conditions [59, 60], such as heating it above the transition temperature [61], photo-excitation [62], applying an electric-field [63], introducing dopants [64], or applying strain to the VO_2 film [65]. The phase transition is ultrafast and abrupt, and as such, VO_2 is very suited to be implemented as threshold devices.

VO_2 exists in two forms depending on whether an external perturbation (as has been described above) is applied. In the monoclinic form (or the rest state), it is a dispersive insulator ($\text{VO}_2\text{-I}$) with a refractive index of $n = 3.243 + 0.3466i$, while in the tetragonal form (the excited state), it is a lossy semi-metal ($\text{VO}_2\text{-M}$) with a refractive index of $n = 1.977 + 2.53i$, at the wavelength of 1550nm. This large contrast in the refractive index is the reason why VO_2 attracted a lot of attention in the design of

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optical modulators and switches. For example, the authors in ref. [66] implemented VO₂ switching material into a photonic ring resonator and achieved a 6.5dB modulation. The authors in ref. [67] implemented VO₂ plasmonic waveguides to obtain a 20dB modulation. The authors in ref. [68] managed to get a modulation depth as high as 6.1dB/μm using a hybrid VO₂ waveguide structure.

The switching speed of VO₂ is projected to be at timescales of picoseconds or faster [60], hence giving the prospects of building ultrafast devices. In the case of optoelectronic modulators, the phase-transition threshold electric-field is experimentally determined to be in the range from 10MV/m to 65MV/m [63, 69]. These moderately-high electric-field thresholds can be easily overcome by applying the bias voltage across very narrow gap-widths through the use of plasmonic structures.

4.3 VO₂ plasmonic waveguide and ring resonator modulators

The large refractive index contrast of VO₂ manifests in both the real refractive index and the extinction coefficient. This actually allows us to design various types of modulators. For example, we could adopt the real refractive index approach to design resonator-based modulators like ring modulators. On the other hand, if we used the extinction coefficient approach, we could design waveguide electroabsorption modulators.

4.3.1 VO₂ plasmonic waveguide electroabsorption modulator

The schematic of the VO₂ plasmonic waveguide electroabsorption modulator is shown in Figure 4.1. Light of 1550nm wavelength is coupled from a silicon photonic waveguide of 400nm×220nm cross-section. The light is gradually funnelled into the

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modulator by a copper–silicon–copper plasmonic tapered coupler. Here our choice of metal is copper for reasons of its low propagation losses and CMOS compatibility [70]. Modulation occurs in the short copper–VO₂–copper slot, and the output is funnelled back again into the silicon photonic waveguide by a tapered coupler. Each of the optimized couplers has a 0.5dB coupling loss.

Figure 4.1: VO₂ plasmonic waveguide electroabsorption modulator.

For this modulator, since the extinction coefficient of the insulating VO₂ is lower than that of the semi-metallic VO₂, we will refer to the former as the “on” state and the latter as the “off” state. Then, the insertion loss is defined as the losses of the modulator in the "on" state, while the modulation depth is defined as the losses of the modulator in the "off" state less the losses in the "on" state. The insertion loss and modulation depth of the modulator are plotted in Figure 4.2(a), which recorded 10dB/μm for the former and 50dB/μm for the latter respectively. Meanwhile, Figure 4.2(b) shows the dependence of both the insertion loss and modulation depth on the modulator width. It is seen that at very narrow widths (<20nm), due to tight confinement of the surface plasmon modes inside the MIM structure, the modulator suffers from high losses. The losses can be alleviated by relaxing to broader widths, but this will result in tradeoffs of higher required drive-voltages and larger device

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footprints. Overall, the VO_2 plasmonic waveguide modulator shows a good modulation depth but with a relatively high insertion loss.

Figure 4.2: (a) Insertion loss and modulation depth of the VO_2 plasmonic waveguide electroabsorption modulator. (b) Insertion loss and modulation depth as a function of the modulator width.

4.3.2 VO_2 plasmonic ring resonator modulator

Figure 4.3: (a) VO_2 plasmonic ring resonator modulator. (b) Transmission spectra of the unmodulated ($V=0\text{V}$) and modulated ($V=2\text{V}$) VO_2 plasmonic ring resonator modulator.

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For the VO₂ plasmonic ring resonator structure in Figure 4.3(a), the VO₂ layer is casted as a thin ring encapsulated in a dielectric cladding and then embedded into a copper substrate. Due to the dispersive nature of VO₂ insulator, the VO₂ ring has to be kept thin and the dielectric encapsulation has to be thick in proportion, in order to obtain a fair Q-factor. As such, we design the VO₂ ring to be only 5nm in width, and the silica dielectric is filled in to get a total ring width of 30nm. The inner radius is set as 280nm to obtain the transmission notch at 1550nm wavelength in the “off” state. The whole ring is coupled to a 100nm-wide silicon plasmonic waveguide, separated by a small gap of 10nm.

Figure 4.3(b) shows the modulation performance of the VO₂ ring resonator. When unbiased, it is in the “off” state, having a –4dB transmission notch at 1550nm wavelength. Assuming that the threshold switching field to be 65MV/m, when a 2V drive-voltage is applied, the insulating VO₂ switches to the semi-metal state, acquiring a lower refractive index and red-shifts the resonance by 30nm. Because the semi-metal VO₂ also acquires a higher extinction coefficient, the Q-factor is heavily reduced as well: the transmission notch at 1580nm is only –2.3dB. Overall, at the 1550nm wavelength, the acquired modulation depth is only 2.4dB, with an insertion loss of 1.6dB. As such, for practical purposes, the VO₂ ring resonator may not be a good structure for modulators, because the performance of ring modulators is highly dependent on their Q-factors.

4.4 VO₂ dual-mode plasmonic waveguide electroabsorption modulator

Figure 4.4 shows the design of a VO₂ dual-mode plasmonic waveguide electroabsorption modulator. The modulator structure is largely similar to the VO₂ plasmonic waveguide electroabsorption modulator described in subsection 4.3.1, but

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there are thin, lossless dielectric layers that separate the VO₂ waveguide as well as the silicon tapers from the metal layers, taking the form of a metal–insulator–VO₂–insulator–metal (MIVIM) waveguide structure. This type of waveguide structure is inspired by our recently fabricated multi-layered plasmonic slot waveguides through CMOS compliant processes [71, 72].

Figure 4.4: VO₂ dual-mode plasmonic waveguide electroabsorption modulator.

The lossless dielectric layers function to reduce the insertion losses that is incurred from the lossy VO₂ insulator by redistributing the plasmonic mode from the VO₂ core layer to the dielectric layers. As such, in general, the refractive index of the dielectric layers should be lower than that of the VO₂ insulator layer so as to excite the hybrid plasmonic mode.

4.4.1 Structure design

The waveguide losses depend on the VO₂ and dielectric layer widths. We will use SiO₂ as an example dielectric material to illustrate this. Figure 4.5 shows the insertion loss and modulation depth as a function of both the VO₂ and SiO₂ layer widths. As expected, both parameters increase with increasing VO₂ widths and decrease with increasing SiO₂ widths. Judicial selection of the layer geometries would require taking

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tradeoffs of low insertion loss, high modulation depth, and low drive-energies into consideration, and also to meet device performance specifications. For our purpose of illustration, we use a VO₂ width of 50nm and dielectric widths of 10nm each.

Figure 4.5: (a) Insertion loss as a function of VO₂ and SiO₂ layer widths. (b) Modulation depth as a function of VO₂ and SiO₂ layer widths.

4.4.2 Dual-mode operation

Table 4.1: Three dielectric layer materials and their relationships with the two phases of VO₂

VO ₂ insulator phase (VO ₂ -I), $n = 3.243 + 0.3466i$		
VO ₂ metallic phase (VO ₂ -M), $n = 1.977 + 2.53i$		
SiO ₂ , $n = 1.44$	TiO ₂ , $n = 2.7$	Ge, $n = 4.27$
$n_{SiO_2} < n_{VO_2-M} \quad n_{VO_2-M} < n_{TiO_2} < n_{VO_2-I} \quad n_{VO_2-I} < n_{Ge}$		

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So far, in the previous section [4.3](#), we have shown how we can either use the real part of the VO₂ refractive index to build resonant devices, or use the extinction coefficient to build absorption devices. Here, however, we will explore the potential of the dual-mode waveguide to exploit both parts of the VO₂ refractive index to build an entirely new type of modulator. The dual-mode modulator is able to perform mode-switching between low-loss hybrid plasmonic modes and high-loss MIM modes when VO₂ is switched from “on” to “off”, thereby augmenting the modulator performance when the right design is used.

The performance of the VO₂ dual-mode modulator is heavily influenced by the dielectric layer refractive index. Table 4.1 shows the refractive index relationships of three dielectric materials with the two phases of VO₂. In essence, there are 3 categories of dielectric materials we can use, which is: $n_{\text{dielectric}} < n_{\text{VO}_2-\text{M}}$, $n_{\text{VO}_2-\text{M}} < n_{\text{dielectric}} < n_{\text{VO}_2-\text{I}}$ and $n_{\text{VO}_2-\text{I}} < n_{\text{dielectric}}$. The relationship of dielectric material with VO₂ will determine whether the modulator operates in the hybrid plasmonic or MIM mode. For example, when $n_{\text{dielectric}} < n_{\text{VO}_2-\text{M}}$, the modulator operates in the hybrid plasmonic mode for both the insulator and semi-metal states of VO₂. Therefore, the modulator using this category of dielectric materials experiences very low losses in both the “on” and “off” states. The reverse happens for $n_{\text{VO}_2-\text{I}} < n_{\text{dielectric}}$ as the modulator operates in the MIM mode for both states of VO₂, therefore experiencing very high losses in both states.

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Figure 4.6: Dual-mode plasmonic waveguide with TiO_2 dielectric layers operating in the hybrid plasmonic mode (left) when VO_2 is insulating, and MIM mode (right) when VO_2 is semi-metallic.

The dielectric refractive index in the $n_{\text{VO}_2-\text{M}} < n_{\text{dielectric}} < n_{\text{VO}_2-\text{I}}$ category is a special case. For this category, in the “on” state the device operates in the hybrid plasmonic mode due to the refractive index of the dielectric cladding layers being lower than that of the insulating VO_2 core layer. On the other hand, in the “off” state, the device operates in the MIM mode due to the semi-metallic VO_2 refractive index being lower than that of the dielectric layers. The mode distributions of both states are illustrated in the electric-field maps in Figure 4.6. In the hybrid plasmonic mode, the surface plasmon modes are tightly confined in the low loss cladding layers, thus the insertion loss is greatly reduced in the “on” state. When switched to the MIM mode, the surface plasmons modes are relaxed into the VO_2 core layer, thus increasing the loss in the “off” state. We describe this device as a “dual-mode” waveguide owing to its unique mode-switching characteristics.

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Figure 4.7: Insertion loss and modulation depth as a function of dielectric refractive index (left axis). Modulation depth – insertion loss ratio is used as a figure-of-merit (right axis).

Figure 4.7 illustrates the advantages of having a mode-switching operation. While the insertion loss increases linearly with dielectric refractive index as expected, the main benefit comes from the rapid increase of modulation depth in a sigmoid fashion. The large gain in modulation depth, especially in the $n_{VO_2-M} < n_{\text{dielectric}} < n_{VO_2-I}$ region, directly translates to large gains in modulating performance. For instance, the size of the device and the drive power can be significantly reduced. The figure-of-merit of the modulator, taken as the modulation depth – insertion loss ratio, is also plotted in the same figure. As expected, the best ratio occurs in the $n_{VO_2-M} < n_{\text{dielectric}} < n_{VO_2-I}$ region, validating that effective mode-switching operation requires a stringent selection of the cladding layer materials from this dielectric refractive index category.

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4.4.3 Case studies: SiO_2 , TiO_2 and Ge dielectric materials

Table 4.2: Modulation depth to insertion loss ratio of various VO_2 dual-mode plasmonic waveguide modulators

	Dielectric layer material			
	No slot	SiO_2	TiO_2	Ge
Insertion Loss (dB/ μm)	10	2	5	8
Modulation Depth (dB/ μm)	50	13	45	57
Ratio	5.0	6.5	9.0	7.1

Here we will discuss a few example dielectric layer materials to be used in the design of the dual-mode waveguide modulator: SiO_2 , TiO_2 and Ge. The previous Table 4.1 has shown us their respective relationship categories with VO_2 . Meanwhile, Table 4.2 shows their respective modulation performances in terms of insertion loss, modulation depth and their ratio. The “No slot” column refers to the simple VO_2 plasmonic waveguide modulator as described in subsection [4.3.1](#). It is observed that the simple waveguide modulator shows the poorest ratio performance at only 5.0, while TiO_2 , belonging to the $n_{\text{VO}_2-\text{M}} < n_{\text{dielectric}} < n_{\text{VO}_2-\text{I}}$ category, shows the highest ratio performance at 9.0. These findings are consistent with our design predictions.

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Figure 4.8: Refractive index-normalized lateral electric-field profiles for the “on” and “off” states of the VO₂ dual-mode waveguide modulator, using dielectric materials a) SiO₂, b) TiO₂ and c) Ge.

We also examine the mode distributions in the “on” and “off” states of the VO₂ dual-mode waveguide modulator using the three different dielectric materials, shown in Figure 4.8. As expected, the modulator using SiO₂ dielectric layers displays hybrid plasmonic modes in both states, where the surface plasmon modes is confined in the dielectric cladding layers, as shown in Figure 4.8(a). Mode-switching operation is observed clearly in the modulator using TiO₂ dielectric layers, displaying hybrid plasmonic modes in the “on” state, and MIM modes in the “off” state, as shown in Figure 4.8(b). And finally, the modulator using Ge dielectric layers display MIM modes in both states, where the surface plasmon modes occupy mainly the VO₂ core layer, as shown in Figure 4.8(c).

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4.5 Switching voltages and energies

The switching voltage and energy are also major performance indicators of the VO₂ modulators. Here we limit our discussion to mainly the VO₂ waveguide modulator and dual-mode waveguide modulator. We assume that VO₂ has a switching threshold field of 65MV/m [63], the device is 220nm thick and 200nm long, and energy consumption of the modulators is split into three components: capacitive loss across the insulating VO₂ layer, joule heating loss from leakage currents inside the semi-metallic VO₂, and capacitive loss across the silicon tapers. The dielectric layer material used in the dual-mode waveguide is assumed to be TiO₂.

4.5.1 Switching voltage and energy of the VO₂ plasmonic waveguide modulator

Calculation of the switching voltage and energy of the simple waveguide modulator is straightforward. For a 50nm VO₂ width, the drive-voltage is computed as 3.3V. The capacitive loss across the VO₂ layer is given as:

$$\frac{1}{2}CV^2 = \frac{1}{2}\frac{\epsilon\epsilon_0 A}{d}V^2 \quad (4.1)$$

Using ϵ (VO₂-I, constant) ≈ 36 [73], and ϵ_0 is the permittivity of free space, we can calculate the loss to be 1.53fJ/bit. Similarly, we can also calculate the capacitive losses of the silicon tapers, each at 0.113fJ/bit, with the assumption of the tapers being 200nm in length and have an average width of 225nm, and using ϵ (Si, constant) ≈ 12 . The joule heating loss, meanwhile, is given by:

$$\frac{V^2}{RB} = \frac{V^2}{\left(\frac{\rho d}{A}\right)B} \quad (4.2)$$

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Using ρ (VO₂-M) $\approx 1\Omega\text{m}$ [74], and assuming $B = 1\text{GHz}$ operating bandwidth, we can estimate the joule heating loss to be 9.6fJ/bit. Overall, the device is estimated to consume a total of 11.4fJ/bit. Most of the energy wastage comes from the joule heating loss ($> 84\%$).

4.5.2 Switching voltage and energy of the VO₂ dual-mode waveguide modulator

Since the additional 10nm dielectric cladding layers adds to the width of the dual-mode waveguide, there is a slight increase of the drive-voltage to 4.6V. Using Eqn. (4.1), we can estimate the capacitive losses of the waveguide as well as the silicon tapers to be 2.12fJ/bit and 0.22fJ/bit each, respectively. The joule heating loss from leakage currents is expected to come from electron-tunnelling through the 10nm TiO₂ layer. The tunnelling current, I_t , is given by [75]:

$$I_t = A \cdot K_1 E^2 \exp - \frac{K_2 \left[1 - \left(1 - V/\phi \right)^{3/2} \right]}{E} \quad (4.3)$$

where $K_1 = q^3 / (16\pi^2 \hbar \phi)$, $K_2 = 4\sqrt{2m_e^*} \phi^{3/2} / (3\hbar q)$, $\phi = 4.8\text{eV}$ is the tunnelling barrier height of TiO₂ [76], q is the electronic charge, $\hbar$ is the reduced Planck's constant, $m_e^* = 3m_0$ is the electron effective mass in TiO₂ [77], and m_0 is the electron free mass. Evaluation of Eqn. (4.3) shows that the value is essentially zero. Hence, the overall energy consumption of the dual-mode waveguide modulator is only 2.6fJ/bit, a substantial reduction from the case of the simple waveguide modulator.

4.6 Conclusions

In this chapter, we have discussed the unique properties of VO₂, and leveraged its large refractive index change to build waveguide electroabsorption as well as ring

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resonator modulators. The large refractive index contrast of VO₂ also enabled us to go beyond the design of traditional modulators (i.e. the modulator design approach that is either from the real refractive index or the extinction coefficient but not both). We have proposed a novel VO₂ dual-mode plasmonic waveguide modulator that can combine the modulation effects from both parts of the refractive index. The dual-mode modulator employs a mode-switching operation to switch between a low-loss, hybrid plasmonic mode in the “on” state to a high-loss, MIM mode in the “off” state, therefore significantly lowers the insertion loss, enhances the modulation depth and improves the overall modulation depth to insertion loss ratio. We have designed a VO₂ dual-mode plasmonic waveguide modulator that is ~200nm ($\sim\lambda/8$) in length, with a corresponding ~1dB insertion loss and ~10dB modulation depth. This device requires a drive-voltage of 4.6V and only consumes energy of 2.6fJ/bit.

Chapter 5

Active Graphene Nanoribbon Plasmonic Waveguide Devices

Besides VO_2 , graphene is recently found to be an excellent switching material. In this chapter, we introduce doped graphene as a potential active plasmonic switching material, which has an unprecedented large tunability of its permittivity-function, and hence could concurrently replace metal-based plasmonics and dielectric switching media. We first analyze the frequency-dependent optical properties of graphene, which are also affected by factors such as their chemical potentials and finite nanoribbon widths. We then propose a few Figure-of-Merit (FoM) formulae to characterize the waveguide performance of the graphene sheets and nanoribbons. Based on these FoMs, we design active thin film graphene nanoribbon (GNR) plasmonic waveguides, which will lead to a variety of GNR plasmonic optoelectronic devices. A simple waveguide plasmonic modulator is first designed as a precursor to more complex devices, which can be switched on/off depending on the applied voltage. The waveguide plasmonic modulator is then used as the basic element to build active power splitters based on GNR cross-junction waveguides. The GNR cross-junction waveguides can be further scaled up to become large and complex networks, paving the way for doped graphene to be used in ultracompact mid-infrared integrated plasmonic nanocircuits.

5.1 Graphene as an active plasmonic material

Ever since graphene has been recognised for its importance in science and technology, it had been earmarked in a roadmap for a myriad of important

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applications, including but not limited to nanoelectronics, nanophotonics, paints and coating, energy generation and storage, as well as sensors in biotechnology applications [78]. In the areas of optoelectronics, graphene had been widely researched for implementation in photodetectors [79], optical modulators [80], optical polarizers [81], and also THz lasers [82].

Graphene is a naturally-occurring, atomically-thick two-dimensional material [78]. The unique nature of graphene manifested in its various interesting material properties. For example, pristine graphene has an electronic structure where the conduction and valence band meets conically at the Dirac point. Consequently, there is no band gap in pristine graphene, which gives rise to a universal optical absorption figure of $\pi\alpha = 2.3\%$, where α is the fine structure constant [83]. Graphene thus shows broadband and high unit-volume absorption compared to most common materials, which is suitable to make highly efficient photodetectors.

The main strength of graphene, however, is manifested in its doped form. When graphene is doped with a certain level of electron or hole concentration, it exhibits a metallic nature, and hence supports surface plasmon modes [84]. This has been demonstrated both theoretically [85, 86] and experimentally [57, 87]. The existence of plasmons in graphene made it a potential platform for graphene-based plasmonic devices. The advantage of using graphene plasmonics for devices lies in the highly compact graphene surface plasmon (GSP) wavelength, which is compressed from free-space wavelengths down by two to three orders [84–87]. This has, for the first time, opened up a potentially huge research area for ultra-compact integrated optics solutions. For example, mid-infrared devices, which are usually

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cubic-micrometers in volume, could be implemented in deep submicron scales using graphene plasmonics.

Another great advantage of graphene-based plasmonics lies in the versatile control of doped graphene's permittivity-function. Graphene's permittivity can be tuned either via chemical doping [88] or external electric-fields [89], thus graphene emerges as an excellent platform for active optoelectronic devices. This property is unprecedented in metals, as we have seen from literature that most metal-based active plasmonic devices require an active nonlinear dielectric switching medium [16]. As such, our interest here is to leverage the large tunability of graphene to build graphene nanoribbon (GNR) plasmonic waveguide modulators. The waveguide modulators can then be expanded to build active power splitters and then scaled up to large and complex active GNR networks.

5.2 Optical properties and waveguide performance of graphene

Here we shall discuss on the optical properties of doped graphene that gave rise to its plasmonic activity. The waveguide performance of graphene sheets and nanoribbons will also be discussed.

5.2.1 Optical properties of graphene

The optical properties of graphene can be described by the dynamic optical conductivity of graphene $\sigma(\omega) = \sigma'(\omega) + \sigma''(\omega)$ obtained from the Kubo formula [85, 86], which has an intraband contribution:

$$\sigma_{\text{intra}}(\omega) = \frac{ie^2\mu}{\pi\hbar^2(\omega + i\tau^{-1})} \quad (5.1)$$

and an interband contribution:

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$$\sigma_{\text{inter}}(\omega) = \frac{ie^2}{4\pi\hbar} \ln \left(\frac{2|\mu| - (\omega + i\tau^{-1})\hbar}{2|\mu| + (\omega + i\tau^{-1})\hbar} \right) \quad (5.2)$$

where i is the imaginary unit, e is the electronic charge, μ is the chemical potential, $\hbar$ is the reduced Planck's constant, ω is the radian frequency, and $\tau = 0.5\text{ps}$ is the relaxation time. The equations are valid under the condition $|\mu| \gg k_B T$, where k_B is the Boltzmann constant, and T is the temperature. Under room temperature, μ should be much larger than 26meV for the description to be accurate. From the optical conductivity, we can further establish the drude permittivity-function:

$$\varepsilon(\omega) = 1 + \frac{i\sigma}{\varepsilon_0 \omega \Delta} \quad (5.3)$$

where ε_0 is the permittivity of free space, and Δ the effective thickness of the graphene sheet, introduced into the drude equation as a technique to recover the volume permittivity of monolayer graphene [90].

From the optical conductivity of graphene, we can predict the existence of two propagation modes [85]. The first is the graphene surface plasmon (GSP) mode, also called the transverse-magnetic (TM) mode, which is supported whenever $\sigma''_{\text{intra}} > 0$ and hence a non-zero μ is required. The other mode is the transverse-electric (TE) mode, which is supported when $\sigma''_{\text{inter}} < 0$ and $\hbar\omega/2 > |\mu|$. Taken together, the GSP modes are permitted when $\sigma''(\omega) > 0$, and disallowed when $\sigma''(\omega) < 0$. Since the optical conductivity of graphene is influenced by μ , switching between allowed and cutoff modes is possible by switching μ alone. As mentioned before, active switching of the optical conductivity is possible since μ can be switched by an electric-field, which is described by the equation [89, 91]:

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$$\mu = \hbar v_F \sqrt{\frac{\pi \epsilon \epsilon_0}{e}} E \quad (5.4)$$

where $v_F = 10^6$ m/s is the Fermi velocity, ϵ is the dielectric spacer relative permittivity, and E is the electric-field.

5.2.2 Waveguide performance of graphene sheets

The optical conductivity can be further used to obtain waveguide performance parameters. Assuming the graphene sheet to be free-standing, the guided plasmon wave vector equation is given as:

$$\beta^2 = k_0^2 \left[1 - \left(\frac{2}{\eta_0 \sigma} \right)^2 \right] \quad (5.5)$$

where k_0 is the free space wave vector and $\eta_0 = 377\Omega$ is the intrinsic impedance of free space. From the guided plasmon wave vector β , we can determine the GSP wavelength, given by $\lambda_{GSP} = 2\pi/\text{Re}(\beta)$, and also the propagation length, given by $L_{GSP} = 1/\text{Im}(\beta)$.

In plain terms, $\text{Re}(\beta)$ represents the confinement strength of the GSPs that results in the free-space wavelength compression, while $\text{Im}(\beta)$ represents the losses of the guided modes. Taken together, we can define the figure-of-merit (FoM) of the guiding performance of graphene sheet, given as [92]:

$$\text{FoM}_1 = \frac{\sqrt{\text{Re}(\beta) \cdot k_0}}{2\pi \text{Im} \beta} = \frac{L_{GSP}}{\sqrt{\lambda_{GSP} \cdot \lambda_0}} \quad (5.6a)$$

FoM_1 is plotted with respect to the operating free space wavelength λ_0 and chemical potential μ as shown in the contour plot of Figure 5.1(a). Using this metric, graphene has the best waveguide performance in the short λ_0 and high μ regime.

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However, this metric is not suitable for highly-doped graphene, which is obtained either through complex chemical doping methods [88], or maintaining high electric-fields as has been evaluated in Eqn. (5.4). Therefore, it is imperative for us to define a new FoM to take into account the normalization factor of μ (in units eV), proposed as:

$$\text{FoM}_2 = \text{FoM}_1 / \mu[\text{eV}] \quad (5.6b)$$

The FoM_2 contour plot is shown in Figure 5.1(b). After using the μ normalization factor, it is shown that waveguide performance of graphene in the low μ and mid-infrared λ_0 regime is comparable to that in the high μ and short λ_0 regime. As such, we have the liberty to choose between low-doped or high-doped graphene for various λ_0 , depending on specific device applications.

We also need to remember that we are using graphene for active waveguide modulators, and thus it is vital to consider the switching performance in the design. Therefore, two additional FoMs are proposed here, which are respectively for the two modulation schemes available: phase modulation or absorption modulation. The FoM for phase modulation takes into account how large the permittivity-function of graphene can be switched per unit μ of 0.1eV, given as:

$$\text{FoM}_3 = \text{FoM}_2 \times \frac{\Delta\lambda_{GSP}}{\lambda_{GSP}} \quad (5.6c)$$

Meanwhile, the FoM for absorption modulation is defined as the magnitude of propagation length that can be changed per unit μ of 0.1eV, given as:

$$\text{FoM}_4 = \text{FoM}_2 \times \frac{\Delta L_{GSP}}{L_{GSP}} \quad (5.6d)$$

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Both FoMs are plotted in Figure 5.1(c) and (d). It is observed that the active waveguide performance is particular good in the low μ ($< 0.3\text{eV}$) and mid-infrared λ_0 (6–10 μm) regime. Thus, taking both the performances of passive and active waveguides into consideration, we would design our graphene waveguides using $\lambda_0 = 10\mu\text{m}$ and $\mu = 0.2\text{eV}$ operating parameters. For discussion simplicity, we will only use an absorption modulation switching scheme.

Figure 5.1: FoM contour plots for graphene sheet using (a) standard definition, (b) FoM normalization to μ , and FoMs taking active waveguiding into consideration using (c) phase modulation and (d) loss modulation. The gray areas in all plots indicate that graphene surface plasmons are at the cutoff state.

5.2.3 Waveguide performance of graphene nanoribbons

The discussions in the previous section are valid for infinite graphene sheets. For finite graphene nanoribbons (GNRs), however, λ_{GSP} , L_{GSP} , as well as the FoMs are

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further modified due to the presence of edge modes, as have already been discussed in detail for finite metal strips as well as graphene microribbons [93, 94]. The edge-mode modification of the GNR waveguide performance is heavily dependent on the GNR width, as will be shown below.

Figure 5.2: (a) λ_{GSP} , L_{GSP} and (b) FoM_2 and FoM_4 as a function of GNR width. (c) Z-direction (TM) and (d) y-direction (TE) electric-field components of the fundamental propagation mode of a 30nm-wide GNR. Together they form the TEM mode.

For a $\lambda_0 = 10\mu m$ and $\mu = 0.2eV$ graphene sheet, λ_{GSP} and L_{GSP} is around 200nm and $2.6\mu m$ respectively, as can be calculated from Eqns. (5.1)–(5.5). For a finite GNR, however, both values are lowered considerably, as reflected in the plot from Figure 5.2(a). For wide ribbons (100–250nm), the λ_{GSP} is in the range of 150–160nm. As the ribbon width gets narrower, the increased coupling between the overlapping edge modes further increases the confinement strength of the GSP and hence further reduces λ_{GSP} . The edge mode is classified as a unique TEM mode, as shown in Figure

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5.2(c) and Figure 5.2(d). Waveguide losses are increased as well, reflected from the L_{GSP} values. Furthermore, the FoMs are affected as well, as can be seen from Figure 5.2(b). From the FoM₂ and FoM₄ trends in Figure 5.2(b), we can easily pick the best performing GNR waveguide widths, which happens to be around 30–50nm. We will choose a GNR waveguide width of 30nm for all of the designs of our active GNR waveguide devices in the subsequent sections, which has a corresponding $\lambda_{GSP} \approx 120\text{nm}$ and $L_{GSP} \approx 1.9\mu\text{m}$.

5.3 Simulation methodology

As graphene is a 2-D material, we cannot directly model the graphene parameters on a 3-D software environment. First and foremost, graphene has a 2-D optical conductivity, and thus lacks a 3-D "permittivity". However, we are able to define a "pseudo" permittivity by applying the technique proposed by Vakil and Engheta [90]. We first assume that graphene has a finite thickness Δ , and thus we can get its volume conductivity, σ/Δ . Applying the volume conductivity, we get the permittivity of graphene as found in Eqn. ((5.3).

Next, we need to define this thickness of graphene. Since this is not the real thickness of graphene, only to be used for simulation purposes, we can arbitrarily define it as 1nm [90]. With this we can get the corresponding permittivity. However, it should be noted that this permittivity should be strictly used in conjunction with the 1nm-thick graphene in the 3-D simulation and not with other thickness values.

We have tested this method in our simulation of the graphene sheet, and found a very close match between the simulated and the analytical value of the guided plasmon wave vector β .

5.4 Design of active graphene waveguide devices

In the following subsections, we will first discuss the design of a plasmonic waveguide modulator, whereby the GNR waveguide can be switched on or off by means of gate-voltage biasing. Then, we will use the plasmonic modulator as the basic element to build an active 4-port GNR plasmonic power splitter, which is made out of cross-junction waveguides. Finally, we can further scale up the active power splitter into a 2×2 array of cross-junction waveguides, which essentially becomes an 8-port cascaded power splitter. Following this template, further mass-scaling is possible to build large and complex active GNR waveguide networks.

5.4.1 Graphene waveguide plasmonic modulators

Figure 5.3: A graphene waveguide plasmonic modulator, which consists of a GNR placed on top of an inhomogeneous SOI substrate. Intensity plots along the x-direction before and after modulation are shown.

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The graphene waveguide plasmonic modulator, which is shown in Figure 5.3, consists of a GNR which is placed on top of an inhomogeneous silicon-on-insulator (SOI) substrate [90]. At the operating wavelength of $10\mu\text{m}$, the dielectric permittivity of silicon (Si) and silicon dioxide (SiO_2) are 11.7 and 2.1 respectively [95]. At the middle of the SOI substrate, there is a Si nanopillar gate which has dimensions of $30\text{nm} \times 50\text{nm} \times 100\text{nm}$, buried in the SiO_2 substrate. The Si nanopillar provides the grounding level which is distinct from the grounding levels for the rest of the waveguide. The GNR is separated by a 10nm SiO_2 gap from the Si nanopillar tip. λ_{GSP} is further scaled down to $\sim 80\text{nm}$ because the GNR is no longer free-standing, but surrounded by an unsymmetrical air- SiO_2 /Si substrate background material.

The GNR is chemically doped to $\mu = 0.2\text{eV}$ [96], so that under an unbiased condition, GSP can propagate along the waveguide. When a gate-voltage is applied across the SiO_2 gap, the chemical potential of the 50nm GNR waveguide portion on top of the Si nanopillar can be reduced and its propagation switches to cutoff. This can be done, for example, by reducing the chemical potential to $\mu = 0.05\text{eV}$ (or $\Delta\mu = -0.15\text{eV}$, or $E = 0.143\text{V/nm}$, or $V = 1.43\text{V}$). The transmission intensity plot in Figure 5.3 reveals that by switching off the 50nm GNR waveguide, the GSP transmission can be attenuated $\sim -30\text{dB}$ using this modulation scheme.

It is further noticed from the intensity plot in Figure 5.3 that in the unbiased-state, the intensity is higher at the middle of the waveguide where the Si nanopillar is located. This is because the effective refractive index of the waveguide is substantially increased with the presence of the Si nanopillar and the small SiO_2 gap, and as such confinement of GSP is very much higher compared to the rest of the waveguide. This slight mismatch of effective refractive index along the GNR

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waveguide causes a slight reflection loss of 0.3dB. A larger SiO₂ gap could reduce this effect, but we should also consider the tradeoff of a larger gap that translates to a larger required gate-voltage.

When the 50nm middle GNR waveguide is at the propagation cutoff state after biasing is applied, we notice from the intensity plot in Figure 5.3 that there is a large reflection induced at $x = 125\text{nm}$. This reflection of 2dB magnitude comes from the interface between two GNRs with different chemical potentials. While it does not affect the performance of the plasmonic modulator, it will affect the performances of the active power splitter and waveguide network, as will be discussed in the subsequent sections.

5.4.2 Active graphene plasmonic power splitters based on GNR cross-junction waveguides

Figure 5.4: (a) Top view of the GNR cross-junction waveguide. (b) Horizontal cross-section along Port 1 to Port 2 of the cross-junction waveguide.

We shall expand the idea from the simple graphene waveguide plasmonic modulator to build an active power splitter based on a cross-junction waveguide [97]. The top-view schematic of a GNR cross-junction waveguide is shown in Figure 5.4(a), where

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two GNR waveguides intersect perpendicularly with each other. Port 1 is the input port from where the GSPs will enter. The GSPs reaching the intersection will be split accordingly, entering Ports 2–4. This constitutes a basic 4–port active power splitter.

For this active power splitter, we employ Si nanopillar gates embedded in the SOI substrate as shown in Figure 5.4(b), each having dimensions of $30\text{nm} \times 50\text{nm} \times 100\text{nm}$. They are separated by a distance of $2 \times L_b + w$, where L_b is the buffer-zone length and $w = 30\text{nm}$ is the junction length. The Si nanopillars are electrically-isolated so that each waveguide arm can be individually-controlled. Similar to the graphene waveguide plasmonic modulator, the GNRs are doped to $\mu = 0.2\text{eV}$ to enable GSP transmission in the unbiased-state, and modulation of a 50nm waveguide portion to $\mu = 0.05\text{eV}$ switches a waveguide arm to cutoff. Likewise, a waveguide length of only 50nm will be modulated, which gives a good modulation contrast of $> 30\text{dB}$ for each arm.

In principle, the minimum separation length required of the Si nanopillar gates is only the junction length $w = 30\text{nm}$, to enable individual-control of the waveguide arms. However, in our analysis, connecting the active waveguide region directly to the junction poses a problem during the modulation process of one or more waveguide arms. Firstly, the problem of high junction reflection as described in subsection 5.4.1 manifests, reducing the power transmission to the output ports. Secondly, it changes the power-splitting proportion between the transmitting output arms, resulting in an imbalanced power-transmission distribution. These problems can be alleviated by adding a buffer-zone at the vicinity of the cross-junction intersection, which separates the Si nanopillars from the junction by an additional buffer length of L_b . The role of the buffer-zone will be further explained using Figure 5.5.

Figure 5.5: Power transmission at the output ports as a function of buffer length L_b and their corresponding z-direction electric-field maps of GSP propagation on the cross-junction waveguide, with transmission switched on for (a) all output ports (unbiased-state), (b) Port 2 only, (c) Ports 2 and 3, (d) Ports 3 and 4, and (e) Port 3 only. Modulation contrast at propagation cutoff is $> 30\text{dB}$. (f) electric-field map of case (e) is enlarged to clearly illustrate the formation of the stub-like structures when two waveguide arms are switched off.

Figure 5.5(a)–(e) show the power-transmission distributions at the output ports as a function of L_b for 5 modulation scenarios. For each scenario, the transmission is switched on for (a) all output ports, (b) Port 2 only, (c) Ports 2 and 3, (d) Ports 3 and 4, and (e) Port 3 only. When $L_b = 0$, it is noticed that when one or more waveguide arms are switched to propagation cutoff, the junction reflection becomes higher resulting in lower power transmission in scenarios (d) and (e). Additionally, there is

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also an imbalanced splitting-proportion over the output ports in scenario (c). However, this problem is corrected at an optimal L_b range of 15–35nm (shaded regions), where we can see the power transmissions improve in scenarios (d) and (e), and the power-splitting proportions converge in scenario (c). The reason for these improvements can be understood from transmission-line impedance-matching theory. When one or more waveguide arms are switched off, there is a slight protrusion of L_b at the buffer-zone which is still transmitting, as can be clearly seen from Figure 5.5(f). These protrusions form stub-like structures which optimize phase-matching between the input and transmitting output ports. This reduces the reflections and hence power transmission is maximized and balanced over the transmitting output arms [98].

5.4.3 Active graphene plasmonic cascaded power splitters and waveguide networks based on GNR cross-junction waveguide arrays

The basic 4-port active power splitter could be placed in an array to build an active cascaded power splitter. Figure 5.6(a)–(c) show examples of how GSP power transmission can be actively-controlled at the outputs on an 8-port GNR cross-junction waveguide array. Similar to before, the GNRs are doped to $\mu = 0.2\text{eV}$ to enable GSP transmission in the unbiased-state, and modulation to $\mu = 0.05\text{eV}$ switches the waveguide arms to propagation cutoff. The modulation is performed only at the output arms, which is suffice to provide a good modulation contrast (in most cases, attenuation is $> 30\text{dB}$).

In practice, the GNR cross-junction waveguide array can be scaled up into even larger arrays of waveguide networks [99], which opens up pathways to build large and complex graphene plasmonic nanocircuits. The active GNR waveguide network would open up potential possibilities in the design of active and ultracompact

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cascading power splitters, multi-port multiplexers and demultiplexers for multichannel communications.

Figure 5.6: Various z-direction electric-field maps for GSP propagation on an 8-port GNR cross-junction waveguide array. Transmission is switched on for (a) all output ports, (b) Ports 3 and 6, and (c) Ports 4 and 8.

5.5 Proposed fabrication steps

Here we propose possible fabrication steps for the GNR cross-junction waveguide array as shown in Figure 5.7. The Si nanopillars in Figure 5.7(a) can be patterned on an SOI substrate using top-down lithography methods which can be precise in both features and positioning down to the deep-submicron level [100]. After that, a layer of SiO₂ can be deposited to cover the Si nanopillars as shown in Figure 5.7(b). The surface of the SiO₂ can then be polished down to 10nm just above the Si nanopillars

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to define the gate-oxide thickness. A layer of monolayer graphene sheet is then transferred to the SiO_2 surface by an easy stamping process [101], and then chemically doped to 0.2eV, as shown in Figure 5.7(c). Finally, the graphene-on-substrate can be patterned using available graphene lithography techniques to obtain the structure of the 2×2 cross-junction waveguide array shown in Figure 5.7(d) [102, 103]. Most of the fabrication steps discussed here are CMOS compatible, hence enabling the industrial leverage of mass-producing these graphene plasmonic devices in the near future.

Figure 5.7: Fabrication process of the GNR cross-junction waveguide array. (a) Lithographic patterning of Si nanopillars on an SOI substrate. (b) Deposition of SiO_2 . (c) Transfer of graphene onto SiO_2 surface and chemical doping. (d) Lithographic patterning of graphene.

Electrical contacts can reach the pillars by using through silicon vias (TSV) (<http://www.realworldtech.com/3d-integration/>). This is currently a hot topic in 3D stacking technology, and cross-talks between electrical contacts are also one of the major areas of research. The topic is very broad and wide and would be out of the scope of this thesis.

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5.6 Discussion on the choice and applicability of mid-infrared graphene plasmonics

We have shown throughout this chapter that graphene plasmonics utilize the mid-infrared wavelength as its propagation wavelength. However, the conventional wavelength in telecommunications is around 1550nm. We can actually use graphene plasmonics at this telecommunication wavelength as has been already shown in Figure 5.1, albeit with a higher doping concentration requirement which is technologically challenging.

However, our study of mid-infrared graphene plasmonics is exploratory and does not confine to the field of computing and telecommunication devices alone. The mid-infrared wavelengths are very important in the field of biology and thermooptics [104], where they can find applications in thermal sensors and microscopy. As such, our perspective can be broadened in a sense that those devices may incorporate nanocircuitry that also operates in the mid-infrared wavelength. This can allow for smoother integration, since those devices mentioned are independent and do not necessary require the telecommunication wavelength standard for their operation.

Thus, the use of graphene nanocircuits may be able to scale down the size of the mid-infrared devices, and can give added benefits of fast computational power, leading to fast, responsive and low-powered thermal sensors and digital microscopes.

5.7 Conclusions

In this chapter, we have proposed the use of graphene as an excellent active plasmonic material with large tunability of its permittivity-function rarely seen in noble metals. We have discussed on the optical properties of graphene, and

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characterized the waveguide performances of graphene sheets and nanoribbons based on a few proposed FoM formulae. Using the FoMs, we design a waveguide plasmonic modulator which shows modulation contrast of more than 30dB for a 50nm modulator length. The waveguide plasmonic modulator is then extended to an active GNR cross-junction power splitter, which shows independent control of each waveguide arm. It also shows nearly-equal power-splitting proportions even during modulation, which is achieved by the use of plasmonic stub-like structures for phase-matching. The cross-junction waveguide is further scaled up into an 8-port of GNR waveguide network, showing potential in realizing ultracompact mid-infrared plasmonic integrated nanocircuits in deep-submicron dimensions.

Chapter 6

Summary and Outlook

We shall summarize the research milestones we achieved thus far. Thereafter, we shall also identify potential research and development areas for plasmonic optoelectronics by having a broader outlook of current and future research trends across multidisciplinary research fields.

6.1 Summary of research milestones

As electronic integrated circuits continued to scale down in accordance to the Moore's law, the shrinking dimensions of the electrical interconnects had caused increases in power dissipation and data transmission delays. Photonic interconnects were proposed as the leading choice replacement for the electrical interconnects, which promised low-loss, high-speed and huge-capacity data transmission. However, photonic devices hindered the integration of silicon photonic interconnects with electronic transistors due to their sizes, and hence we look towards plasmonics as a complementary bridging technology. By integrating electronics, photonics and plasmonics into the same platform, we could fully exploit the advantages of the three technologies. Our research focused on the design of plasmonic optoelectronic transducers – the plasmonic detectors and modulators – that manipulate light at the subwavelength scale, facilitating seamless integration between photonic waveguides and electronic transistors.

We had designed a monopole antenna-assisted waveguide-integrated plasmonic cavity detector in [Chapter 2](#), having optical power absorption efficiency of up to 42% inside a $220 \times 150 \times 60 \text{ nm}^3$ subwavelength absorption volume. The

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efficiency of the plasmonic detector was optimized by optical power coupling using a resonant monopole antenna and optical power confinement inside a cavity resonator. The plasmonic detector was ultracompact and shown to be easy to fabricate, being perfectly waveguide-integrated and used CMOS compatible materials.

However, we realized that the optical power absorption of 42% is far from ideal. As was discussed in [Chapter 3](#), we found that the significant absorption efficiency loss came from the optical power leakage due to imperfect Fresnel reflections from the cavity resonator. As such, we drew inspiration from coupled-cavities, commonly found in photonic-crystal devices, as a method to improve optical power localization. We had designed two extra components – the coupler cavity and reflector cavity – to efficiently couple and confine surface plasmons inside the detector cavity. As a result from strong, synergized cavity-coupling, optical power absorption of the plasmonic detector was increased to 78%.

We then moved on to design plasmonic modulators in [Chapter 4](#). We had found an efficient switching material – vanadium dioxide (VO_2) – which showed a high refractive index switching contrast, a moderate threshold switching field and an ultrafast switching speed. We applied VO_2 into a simple plasmonic waveguide electroabsorption modulator and a ring resonator modulator and they showed reasonable performances. The landmark achievement was in the design of a novel dual-mode plasmonic waveguide electroabsorption modulator that showed an exemplary device performance, having an ultrashort length of 200nm, a corresponding insertion loss of only 1dB, a large modulation depth of 10dB, a drive-voltage of 4.6V and energy consumption of 2.6fJ/bit. The design leveraged the high refractive index contrast of VO_2 in combination with a multilayered metal–insulator–

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VO₂–insulator–metal (MIVIM) plasmonic waveguide structure. This enabled a mode-switching operating, switching between low-loss hybrid plasmonic modes and high-loss MIM modes, on top of modulating the absorption coefficients of VO₂. In this regard, the dual-mode design went beyond traditional modulator designs that used either phase or absorption modulation schemes: it combined both modulation schemes to enhance the switching performance of the modulator.

Finally, in Chapter 5 we had investigated graphene as a potential active plasmonic switching material for a new class of graphene nanoribbon (GNR) waveguide modulators and other switching devices. Doped graphene possesses a large tunability of its permittivity-function and high confinement unprecedented in noble metals, which eliminates the need for nonlinear dielectric switching media. Thus we had used graphene to design a GNR waveguide plasmonic modulator, which achieved a modulation contrast that exceeds 30dB. We had then extended the GNR waveguide plasmonic modulator to an active cross-junction waveguide power splitter. The cross-junction waveguide was further scaled up into a large and complex array of active waveguide network, showing potential usage in ultracompact mid-infrared plasmonic integrated circuits that operate in deep-submicron dimensions.

The design of these plasmonic optoelectronic devices had successfully scaled down the size of optoelectronics used in electronic–plasmonic–photonic integrated circuits, with bonus benefits such as reduced device energy consumption and higher device speed, arising from their nanoscale footprints. It is optimistic that these devices have the potential for massive-scale industrial realization because they can be fabricated by largely CMOS compatible processes. In addition, specifically for GNR

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devices, they opened up a huge potential for plasmonic devices that operate at the mid-infrared wavelength regime.

6.2 Future outlook in plasmonic optoelectronics research

6.2.1 Major challenges and issues faced by plasmonic optoelectronics

Continuous improvement on the performances of optoelectronics has always been the research goal in the field of photonic–plasmonic–electronic integration. Plasmonic optoelectronic devices are designed on the emphasis of progressively smaller dimensions and energy-consumption footprints, at the same time meeting the minimum requirements of preserving data integrity during the optoelectronic conversions and communications. For instance, in the design of plasmonic detectors, efforts are put in to continually scale down their sizes and operating-powers while maintaining high optical power absorption and response times. In the design of plasmonic modulators, similar efforts are applied while maintaining high modulation contrasts and modulation speeds.

The major challenge faced by plasmonic devices is the incurred optical losses that might degrade data integrity during data transmission and processing. The losses come from a few aspects, for example, metal absorption losses in plasmonic waveguides, and coupling loss when optical power is coupled from photonic waveguides into the devices. These losses were reduced through the use of low-loss metals (e.g. copper) and resonant coupling techniques (e.g. optical antennas and coupled-cavities) as had been presented in our plasmonic device designs. However, continuous reduction of these losses would be necessary if we want to further push the device sizes and energy consumption down to the sub-nm and sub-fJ/bit respectively.

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The continuous research and optimization on traditional plasmonic optoelectronic materials and devices would in time yield only marginal increases in performance, as would be expected of any research areas at their peaks. Therefore, it would also be practical for us to venture beyond the classic in search for more exotic device structures and materials. In the following few subsections, we will briefly give an outlook on two potential research fields for plasmonic optoelectronics: nonreciprocal waveguides and strain-induced nonlinear materials

6.2.2 *Nonreciprocal waveguides enabled by magnetoplasmonics*

One of the main performance problems faced by integrated plasmonic components is that, when assembled, they have lowered coupling, transmission and localization efficiencies due to imperfect impedance-matching. As such, this creates the need for the design of extraneous components to improve those efficiencies, for example, antennas, cavity resonators, quarter-wave couplers and reflectors as have been presented in details in [Chapter 2](#) and [Chapter 3](#). More than often these extra components increase the overall device footprints as a tradeoff for efficiency improvement.

Here we mention a special class of plasmonic component called the magnetoplasmonic nonreciprocal waveguide, which allows surface plasmons to travel in only one direction along the waveguide [105–107]. Using the nonreciprocal waveguides under a strong magnetic field, there is a range of frequencies whereby light is forced to propagate in a single direction. Thus, this has eliminated the need for any antennas or quarter-wave couplers as transmission would be ~100% [107]. To use as a plasmonic detector, it would suffice to enclose the absorption cavity at the

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waveguide end with metallic walls without any special consideration for phase-matching since the optical power would just circulate inside the cavity.

The main technical issue to be solved for these magnetoplasmonic nonreciprocal waveguides is the high magnetic-field bias requirements [106, 107]. This could be resolved, for example, by using suitable, low cyclotron-mass semiconductors (e.g. indium antimonite) to lower the required magnetic bias [107], or by combining magneto-optical materials with plasmonics to strengthen the magnetoplasmonic effect [108]. Interestingly, graphene is also one of the materials that show enhanced magnetoplasmonic activity due to its low cyclotron mass [109], which could potentially be designed as a highly-configurable active nonreciprocal waveguide for mid-infrared operating wavelengths, as an extension of the devices designed in [Chapter 5](#).

6.2.3 *Strained-induced nonlinear materials*

Back in the 1960s, researchers had modelled the electro-optic effect for different types of crystals, and found that the electro-optic coefficients for non-centrosymmetric crystals are very much larger than that for centrosymmetric crystals [110, 111]. Since then it was always assumed that we should only look for nonlinearity in the naturally-occurring non-centrosymmetric crystals such as lithium niobate or barium titanate. However, scientists had recently created an artificial non-centrosymmetric crystal by breaking the crystal-symmetry of silicon using strain [53]. In doing so, they had induced the Pockels effect which is otherwise nonexistent in crystalline silicon, with a 15pm/V nonlinear coefficient. A similar attempt had been made for germanium, which yielded a 280pm/V nonlinear coefficient [112].

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So far, strained-crystals had been used to build photonic modulators and harmonic generators [113–116]. Interestingly, in ref. [115], the authors found that reducing the width of the strained-waveguide silicon photonic modulator increased the performance gain of the device, citing the effect from inhomogeneous strain-distribution. Also, the nonlinear effects are found to be strongest near the strained surfaces. These observations were further corroborated in ref. [116], whereby in a more detailed study, the highest nonlinear coefficients were induced by inhomogeneously-strained silicon waveguides, which generally had rectangular cross-sections coupled with opposing strain directions for the top and bottom strain layers.

Following those developments, we deduce that shrinking down of the strained-waveguide width by using plasmonics could even further increase the induced nonlinear coefficient of the modulator. This is because through the reduction of the waveguide width, more optical power could be concentrated at the strain surfaces, in addition to the ease of designing high aspect ratio waveguide cross-sections. Our speculations could be verified in future either by ab-initio calculations [116] or experimentations.

Author's Publications

International Journals

1. **K. J. A. Ooi**, H. S. Chu, L. K. Ang, and P. Bai, "Mid-infrared active graphene nanoribbon plasmonic waveguide devices," *J. Opt. Soc. Am. B* 30(12), 3111–3116 (2013).
2. **K. J. A. Ooi**, P. Bai, H. S. Chu, and L. K. Ang, "Ultracompact vanadium dioxide dual-mode plasmonic waveguide electroabsorption modulator," *Nanophotonics* 2(1), 13–19 (2013).
3. **K. J. A. Ooi**, P. Bai, M. X. Gu, and L. K. Ang, "Plasmonic coupled-cavity system for enhancement of surface plasmon localization in plasmonic detectors," *Nanotechnology* 23(27), 275201 (2012).
4. **K. J. A. Ooi**, P. Bai, M. X. Gu, and L. K. Ang, "Design of a monopole-antenna-based resonant nanocavity for detection of optical power from hybrid plasmonic waveguides," *Optics Express* 19(18), 17075–17085 (2011).

International Conferences

1. **K. J. A. Ooi**, H. S. Chu and P. Bai, "Active graphene plasmonic waveguides for mid-infrared nanophotonic Circuits," in the 7th International Conference on Materials for Advanced Technologies, 30 June–5 July 2013.
2. **K. J. A. Ooi** and P. Bai, "Subwavelength plasmonic optoelectronic transducers for electronic-photonic integrated circuits," in the 7th International Conference on Materials for Advanced Technologies, 30 June–5 July 2013.

Author's Publications

3. **K. J. A. Ooi**, P. Bai, H. S. Chu and L. K. Ang, “Vanadium dioxide active plasmonics,” in Photonics Global Conference, Singapore, 13–16 December 2012.
4. **K. J. A. Ooi**, P. Bai, M. X. Gu and L. K. Ang, “Compact and efficient plasmonic detector structures for nanophotonic-electronic integrated circuits,” in 5th MRS-S Conference on Advanced Materials, Nanyang Technological University, Singapore, 20–22 March 2012.
5. **K. J. A. Ooi**, P. Bai, M. X. Gu and L. K. Ang, “A plasmonic detector for integrated-circuit applications,” in East Asian Postgraduate Workshop on Nanoscience and Technology, Hong Kong University of Science and Technology, Kowloon Hong Kong, 15–17 June 2011.

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Appendix A

The surface plasmon lifetime inside a resonant cavity is given as:

$$\tau_0 = -\frac{1}{\ln(R_1 R_2)} \quad (\text{A.1})$$

where R_1 and R_2 are the reflectivity of the two interfaces (front and back) respectively. Adding either a coupler cavity (front) or a reflector cavity (back) would increase the reflectivity of the interface. The new surface plasmon lifetime would thus read as:

$$\tau = -\frac{1}{\ln[R_1(1+dR_1)R_2(1+dR_2)]} \quad (\text{A.2})$$

where dR_1 and dR_2 are the increases in reflectivity. For very small dR_1 and dR_2 , $\ln(1+dR) \approx dR$, and thus the equation can be rewritten as:

$$\tau = -\frac{1}{\ln(R_1 R_2) + dR_1 + dR_2} \quad (\text{A.3})$$

We can then rewrite and expand the equation up to the second order using the Taylor expansion $1/(1+x) \approx (1-x+x^2)$:

$$\begin{aligned} \tau &= -\frac{1}{\ln(R_1 R_2) \left[1 + \frac{dR_1 + dR_2}{\ln(R_1 R_2)} \right]} \\ &= \tau_0 \left[1 - \frac{dR_1 + dR_2}{\ln(R_1 R_2)} + \frac{(dR_1 + dR_2)^2}{\ln^2(R_1 R_2)} \right] \end{aligned} \quad (\text{A.4})$$

The change or increase in photon lifetime would thus be:

Appendix A

$$\begin{aligned}
 \Delta\tau &= \tau - \tau_0 \\
 &= \tau_0 \left[-\frac{dR_1 + dR_2}{\ln(R_1 R_2)} + \frac{(dR_1 + dR_2)^2}{\ln^2(R_1 R_2)} \right] \\
 &= \tau_0^2 [dR_1 + dR_2 + \tau_0 (dR_1 + dR_2)^2]
 \end{aligned} \tag{A.5}$$

We can then write the increase of surface plasmon lifetime in the cavity for individual cases. The addition of a coupler cavity at the front would then change the lifetime by:

$$\Delta\tau_{R_1} = \tau_0^2 [dR_1 + \tau_0 (dR_1)^2] \tag{A.6}$$

while the addition of a reflector cavity changes it by:

$$\Delta\tau_{R_2} = \tau_0^2 [dR_2 + \tau_0 (dR_2)^2] \tag{A.7}$$

Here, we can easily sum the two separate increases:

$$\Delta\tau_{R_1} + \Delta\tau_{R_2} = \tau_0^2 [dR_1 + dR_2 + \tau_0 (dR_1)^2 + \tau_0 (dR_2)^2] \tag{A.8}$$

However, the increase in surface plasmon lifetime with the addition of both cavities is given by:

$$\begin{aligned}
 \Delta\tau_{R_1+R_2} &= \tau_0^2 [dR_1 + dR_2 + \tau_0 (dR_1 + dR_2)^2] \\
 &= \tau_0^2 [dR_1 + dR_2 + \tau_0 (dR_1)^2 + \tau_0 (dR_2)^2 + 2\tau_0 dR_1 dR_2]
 \end{aligned} \tag{A.9}$$

and hence, it is proven that the cavity-coupling effect, i.e. the addition of both coupler and reflector cavities can increase the surface plasmon lifetime more than the sum of adding the individual components:

$$\therefore \Delta\tau_{R_1+R_2} > \Delta\tau_{R_1} + \Delta\tau_{R_2} \tag{A.10}$$