Design, analysis and realization of active plasmonic devices

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DESIGN, ANALYSIS AND REALIZATION OF ACTIVE PLASMONIC DEVICES

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School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

2010

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Thesis Summary

This thesis discusses some Surface Plasmon Polaritons (SPPs) based active devices, which form important components of integrated optics. Plasmonics holds promise of realizing devices at nanoscale that are compatible with present CMOS fabrication technology. A complete SPPs based integrated circuit should consist of compact devices that generate, modulate and detect light. In this work, two different designs of plasmonic laser as well as an electro-optic plasmonic modulator have been discussed.

Theoretical models have been developed for an edge-emitting lasing device based on SPPs. An insulator-metal-insulator (IMI) plasmonic waveguide, in which one of the dielectric layers is incorporated with gain, is proposed to realize plasmonic lasing. Finite-difference time-domain studies have been employed to optimize the propagation characteristics of the waveguide by obtaining optimal thicknesses of metal and gain layers. Coupling of SP waves between the top and bottom metal-dielectric interface of the IMI waveguide was observed. Hence, a couple-mode model was developed to analyze the lasing characteristics of the waveguide. The condition to achieve single-mode lasing was then investigated.

This design of IMI waveguide based laser was then extended to realize a random laser based on SPPs. The IMI waveguide was fabricated with Rhodamine 6G (R6G) as gain medium in bottom dielectric layer and a random feedback mechanism was included in top dielectric layer. Photoluminescence studies show random lasing peaks around 590 nm, under 532 nm excitation. Further experiments were designed to

confirm that the random lasing is indeed from the SPPs supported inside the IMI waveguide.

Furthermore, an improved design of plasmonic laser was proposed in which, a metal grating was used to provide feedback and also localize SPPs along the interface of metal and gain layer. A high index decoupling layer was then required to extract the localized SPPs to achieve surface emission. The main advantage of this design is unidirectional emission, unlike the previously proposed structures.

In a metal-insulator-metal (MIM) plasmonic waveguide, if the refractive index of dielectric layer is varied periodically, it can lead to Bragg reflection to the propagating SPPs. This phenomenon was exploited to realize a plasmonic electro-optic modulator. One of the alternating dielectrics was taken to be an electro-optic material so that its refractive index can be varied by external applied field. Modulation studies of electrically controlled Bragg reflector was investigated in detail.

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CHAPTER 1

Introduction

Research in plasmonics has been active nearly for past two decades. Plasmonics, an exciting device technology, exploits the unique optical properties of metallic nanostructures to enable routing and manipulating light at nanoscale by exciting Surface Plasmons Polaritons (SPPs). SPPs are quasi-two-dimensional electromagnetic excitation travelling along a metal-dielectric interface with field component decaying exponentially in two neighboring directions. Renewed interest in plasmonics comes from the recent advances that allow metals to be structured and characterized at nanoscale¹. This in turn reveals the underlying physics of Surface Plasmons (SPs) and enables us to tailor them for specific applications. SPs have shown great potential in optics^{2,3}, magneto-optical data storage⁴, microscopy⁵, solar cell⁶ as well as biological sensors⁷. For researchers in the field of photonics, one of the most attractive features of SPPs is the way in which they help us to concentrate and channel light through a sub-wavelength structure. This could lead to miniaturized photonics integrated circuits with much smaller dimensions than those currently achieved⁸.

1.1 Motivation

Integrated semiconductor electronic industry has witness drastic development in terms of device size and operating speed, which in turn has led them to greater efficiency at reduced costs. Today, state-of-art microprocessor use ultrafast transistors with dimensions of the order 50 nm. Although the speed of these transistors increases

with scaling, the major challenge is carrying the digital signal from one component of microprocessor to the other. In the case of copper wire interconnects, scaling is not sufficient to provide connection for exponentially growing number of transistor. Unlike transistors, for which the performance increases with scaling, the delay of the interconnect increases and becomes a substantial limit to the overall speed of integrated circuits.

Optical interconnects like optical fibers; on the other hand, possess large data carrying capacity compared to their electronic counterpart. Optical alternatives may be particularly attractive for future chips with more data carrying capacity and speed. Unfortunately, their implementation is hampered by large size mismatch between the electronic and dielectric photonic component. The size of dielectric photonic components is limited by the fundamental laws of diffraction. Because of which photonic components tend to be one or two order of magnitude larger than their electronic counterpart. Plasmonics offers solution to this problem. It can offer circuits with nanoscale features which can carry electrical and optical signals simultaneously. The latest advances in electromagnetic simulations and nanofabrication techniques allow the design and use of plasmonic structure in real devices. Current silicon based integrated technology is already used to fabricate metallic nanostructures for electrical interconnects⁹. The same fabrication technique can be extended to manufacture low-cost plasmonic devices.

Over the past decade investigations have proved that creatively designing the metal dielectric interface can generate SPPs of same frequency as that of the electromagnetic radiation generating them but with a much shorter wavelength. This can allow signals to travel in form of SPPs along nanoscale wires called interconnect.

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This will eventually provide the chip designer to develop much faster transistor at very small sizes. At first instance, it seems to be a bad idea to use metallic nanostructures to route optical signals because metals are known to have very high optical loss. An electromagnetic wave striking on the metal surface loses its energy to the abundant free electrons present in the metal. Plasmons on the other hand offer less loss along the interface of metal and dielectric. This is because the field also extends into non-conductive material where the loss due to collision is very less. This property naturally confines SPPs to the interface of metal and dielectric. This planar confinement of electromagnetic waves can be modeled as plasmonic waveguide. With suitable choice of metal and dielectric, electromagnetic waves can be confined to the interface and can be routed along it. In spite of optical signals experiencing losses in the metal, plasmonic waveguides have been found to have propagation distance up to a few centimeters which is enough for transmitting signals within microprocessor or any other photonic integrated circuits. There have been continuous attempts to improve the propagation length and confinement of SPPs. Geometry of plasmonic waveguides has been one of the most important factors to increase their efficiency in terms of propagation distance and mode confinement. The wavelength of SPPs have been reduced to more than a factor of 10 relative to its free-space value with keeping the frequency same. The fundamental principle of frequency times wavelength is equal to speed of light is preserved because electromagnetic waves slow down as they travel along the metal-dielectric interface. This striking ability opens up myriad opportunities to conceptualize various plasmonic devices, ultimately leading to the realization of photonic integrated circuits. Since the frequency of optical signal is very high compared to that of electrical, plasmonic circuits will be able to carry much more data.

A complete integrated circuit based on plasmonics should consist of ultra-compact nanometallic devices that generate, guide and detect light. Efforts have been focused on developing all the three important components. One of the biggest attractions of such nanoplasmonic devices is that the structures are compatible with present CMOS fabrication technology. A tremendous synergy can be achieved by integrating plasmonic, electronic and conventional photonic devices on the same chip and taking the advantages of each technology. Two important aspects of plasmonic chip technology are discussed in details in following section:

1.1.1 Plasmonic Light Source

Plasmonic structures can also revolutionize the lighting industry by making LEDs brighter enough to compete with incandescent bulbs. Plasmonic enhancement of electric field near the metal-dielectric interface can enhance the emission rate of luminescent material present near the metal surface. This effect is more evident in tiny semiconductor emitters like quantum dots and quantum wells¹⁰. Furthermore, plasmonic nanoparticles can also help in developing silicon based light source¹¹. The advantage with silicon is its low manufacturing cost compared to present materials used such as gallium nitride. Silicon based LEDs are currently held back by low emission efficiency of silicon, using plasmonic effect for its enhancement can make silicon shine as bright as present devices. Another important advantage of using plasmonics is that the enhanced emission frequency can be controlled just by changing the size of nanoparticles¹².

Another important class of light source which has attracted great attention is plasmonic analogous to lasers. The quest for ultra compact lasers in nanometer scales

has faced a fundamental obstacle of diffraction limit. For visible light, whose wavelength ranges between 300 and 800 nm, the smallest dimension of both the spot and laser cavity is limited to few hundred nanometers. It is argued that by exploiting a metal-dielectric composite medium, it should be possible to construct a nanodevice, where a strong coherent field is built up in a spatial region much smaller than the wavelength of emitted light. This concept of device was named as surface plasmon amplification by stimulated emission of radiation (SPASER)¹³. This phenomenon is based on excitation of local fields in a nanostructure by a resonant external optical field. It can be fabricated by using quantum dots and metal nanoparticles. Emission from the quantum dots will be localized to the metal-insulator interface and will be amplified by the plasmonic resonator. In case of SPASER, plasmons will be highly localized leading to very low threshold compared to conventional lasing system. These lasing modes are limited to dark modes and hence emit no photons. This implies that a mechanism is required to extract these highly localized plasmons and convert them into emitting photons.

Another important geometry proposed for plasmonic laser is based on metal-insulator interface waveguides. SPPs travelling along the metal-insulator interface experience high propagation loss due to metal layer. This effect is higher in optical ranges of SP compared to mid and far IR structures. One possible solution to this problem is to use a gain medium in the dielectric layer adjacent to the metal layer. This would compensate for the loss occurred due to metal layer, it is also possible to achieve lossless plasmonic waveguides. If a feedback mechanism is also incorporated along with this, laser like emission can be observed. These kinds of devices are similar in concept to that of SPASER but the main advantage is that the SP emission is not

highly localized and lasing photons can be emitted easily. These kinds of multilayered plasmonic lasing devices will be very useful in realizing full photonic integrated circuits. Few important issues remain to be tackled before a full functional plasmonic laser can be realized. One of the most important issues is the degree to which emitted light is coherent. Collimation is also important because of the conversion of SPPs into conventional laser light results into light propagation in all possible directions.

1.1.2 Plasmonic Modulator

Plasmonics presently, is undergoing transition from passive devices to active devices much like historical development of electronic and photonic devices¹⁴. Active devices allow SPPs generated from optical signals to be switched by external electrical and optical stimulus. Over the times, it has been understood that plasmonics holds one of the key roles in developing ultra-compact, high-speed and power efficient optical modulators. One of the simplest ways to modulate SPPs is to control the dielectric property of the insulator layer adjacent to the metal. Propagation characteristics of SPPs highly depend upon the relative refractive index of the two mediums. Both electro-optic and thermo-optic effects have been suggested for this purpose. Using these effects, the dielectric properties of insulator layer can be controlled and SPPs propagation can be modulated. In addition, plasmonic modulator based on quantum dots¹⁵, ferroelectric materials¹⁶ or liquid crystals¹⁷ have also been proposed and demonstrated. However, in terms of integrating this with existing photonic and electronic technologies, it is highly desirable to develop a Si based modulator.

1.2 Objectives

The objectives of this thesis are listed as follows:

- (i) To understand the physics of surface plasmons and explore the possibility of realizing active devices based on plasmonics.
- (ii) To propose and thoroughly characterize a theoretical model for a plasmonic laser.
- (iii) To fabricate and characterize the proposed plasmonic laser and enhance its performance.
- (iv) To improve and modify the model of the laser based on the results from the experiments.
- (v) To propose a theoretical model of SPPs based modulator and optimize its performance.

1.3 Major Contribution of the Thesis

In this work, fundamental characteristics of SPPs propagation along a metal-insulator interface and various other similar geometries have been studied in detail. The studies are then further extended to explore the possibility of realizing plasmonics based active devices. Theoretical models have been developed for an edge-emitting and another surface emitting plasmonic laser. An electro-optic plasmonic modulator based on Bragg-reflector is also modeled. Furthermore, edge emitting plasmonic random laser structure is fabricated based on the design of the developed model. Some of the major contributions of the thesis can be listed as follows:

- (i) An insulator-metal-insulator (IMI) plasmonic waveguide with one of the dielectric layers incorporated with optical gain is proposed to realize plasmonic lasing. Finite difference time domain (FDTD) simulations are

performed to optimize the propagation performance. A coupled-mode model is developed to study the lasing characteristics of the proposed waveguide structure. It was shown that it is indeed possible to achieve single mode plasmonic lasing in this simple geometry ¹⁸.

- (ii) A plasmonic electro-optic modulator is proposed and modeled. The modulator is based on a metal-insulator-metal plasmonic waveguide with periodic variation of refractive index in the insulator layer. One of the insulator layers is taken to be an electro-optic material so that its refractive index can be varied by external applied electric field. SPPs travelling through this device can be modulated by electrically controlling the Bragg reflection of the structure ¹⁹.
- (iii) Experimental realization of plasmonic laser is achieved by fabrication of the proposed structure in model developed. A simpler route compared to the proposed structure in the model was taken by fabricating a random laser based on SPPs. An optical pumped plasmonic random laser was fabricated and the lasing characteristics were studied. The device was shown to have lasing peaks around 590 nm ²⁰.
- (iv) An improved structure of plasmonic laser in which a metal grating is used to provide feedback and localize the SPPs along the interface of metal and gain layer is proposed. A high index decoupling layer is then used to extract the localized SPPs to achieve surface emission. The device is optimized by FDTD calculations ²¹.

1.4 Organization of the Thesis

This thesis is organized as follows: In chapter 2, important achievements in the field of active plasmonics are first discussed. Detailed analysis of recent research

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particularly in the field of plasmonic laser and modulator is then provided. Theoretical background of SPP propagation along metal-insulator interface is discussed and the concept is extended to plasmonic waveguiding. Chapter 3 presents the theoretical model of plasmonic laser proposed. FDTD simulations and coupled-mode theory are employed to design and optimize the proposed structure. In chapter 4, a plasmonic modulator based on electro-optic controlled Bragg reflector is discussed. With the help of developed model the device is characterized for its optimal performance. Next, the experimental study of proposed plasmonic laser is covered in chapter 5. The experimental method is discussed in detail and photoluminescence results are presented. In chapter 6, another model of plasmonic laser is proposed and studied theoretically. The design is compared to the one presented in chapter 3. Similar studies are performed to design and optimize its performance. The works presented in this thesis is summarized in chapter 7 and recommended future work is discussed.

CHAPTER 2

Background and Literature Review

This chapter introduces the concept of surface plasmon polaritons. As metals play the most important role in this field, we start with a short discussion of optical properties of metals based on Drude's model. Next the fundamental properties of SPPs are discussed. Thereafter, the application of SPPs in various devices focusing on plasmonic lasers and modulators are considered in details. A through literature survey is then done to discuss the work done so far in these two areas.

2.1 Optical Properties of Metal: Drude Model

Although a quantum-mechanical treatment is required to understand the properties of metals in detail, a simple classical model developed by Drude in 1900²² is sufficient to describe many properties of metal in present context.

The Drude model is based on kinetic theory of gas. It assumes metal as a collection of non-interacting free electrons having an isotropic effective mass and relaxation time. This implies that electrons move freely between collisions and average rate of collision is inversely related to average relaxation time. Under the

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influence of an external electric field, electrons obey Newton's law of motion and are accelerated between collisions, which lead to drift motion.

Drude model gives us an expression for frequency dependent dielectric constant $\varepsilon(\omega)$ for metals²³:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma} = \varepsilon_R(\omega) + i\varepsilon_i(\omega) \quad (2.1)$$

$$\varepsilon_R(\omega) = 1 - \frac{\omega_p^2\tau^2}{1 + \omega^2\tau^2}, \quad \varepsilon_i(\omega) = \frac{\omega_p^2\tau}{\omega(1 + \omega^2\tau^2)} \quad (2.2)$$

$$\omega_p^2 = \frac{ne^2}{\varepsilon_0 m} \quad (2.3)$$

where, $\varepsilon_R(\omega)$ and $\varepsilon_i(\omega)$ are real and imaginary part of dielectric constant, ω_p is the plasma frequency, determine by electron density n , charge e and mass m . γ is collision frequency and τ is average relaxation time. The relaxation time then can be related to conductivity by expression²⁴.

$$\sigma = \tau \frac{ne^2}{m} \quad (2.4)$$

In Drude model, the dielectric function of a metal is defined only by the plasma frequency and electron collision rate. Typically, the plasma frequency lies in UV region for most of the metals. For example, the plasma frequency in the case of silver is approximately 260 nm. If for some frequency range (optical range), $(\omega\tau^2) \gg 1$, the following approximation can be used:

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$$\varepsilon(\omega) \approx 1 - \frac{\omega_p^2}{\omega^2} \quad (2.5)$$

This implies that above plasma frequency metal becomes transparent ($\varepsilon \rightarrow 1$) while below this frequency it becomes reflective ($\varepsilon < 0$). Metal being reflective leads to exponential decay of electromagnetic field into the metal implying that the light penetrates into the metal only upto the skin depth.

Being a classical model, the Drude model has some limitations. It assumes all the electrons inside the metal are free electrons neglecting the valence electrons which are not free to move. This means that actually metal are not completely transparent or reflective for frequencies higher and lower than plasma frequency respectively. Nevertheless, Drude model gives good agreement with experimental results for most of the metals at optical frequencies. Figure 2.1 compares the experimental data for silver obtained by Johnson and Christy²⁵ with fitted Drude model. It is seen that Drude model is not very accurate at high frequencies.

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Figure 2.1 The real and imaginary part of $\epsilon(\omega)$ for silver determined by Johnson and Christy and Drude model fit to the data²⁶.

2.2 Introduction to Surface Plasmon Polaritons

The interface between metal and another medium can support charge density oscillations. The charge density oscillation and the EM field are coupled to each other and this coupled state is often called an interface or surface polaritons.

The existence of SPPs was first theoretically presented by Ritchie²⁷ in 1957. He described it as a coherent fluctuation of electric charge on a metal boundary. Soon after that, experimental existence of SPPs was demonstrated by energy-loss experiments by Powell and Swan²⁸. The name of the surface plasmon polaritons reflects that the waves are bound to the surface between the two regions with inverse optical properties (e.g. dielectric-metal) and it represents a coupled state between a plasmon, which is associated with longitudinal waves in the collective motion of electrons and free EM field, yielding a polariton type excitation.

To study the propagation characteristics of surface plasmons, we need to start with basic Maxwell's equations. The most common geometry that supports the SPs is a metal-dielectric interface as shown in the Figure 2.2 below.

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Figure 2.2 Geometry of SPs propagation at single interface between metal and dielectric.

The requirement for the metal layer to support SPs is the $\text{Re}[\epsilon] < 0$. For metals this condition is fulfilled at frequencies below the bulk Plasmon frequency ω_p . The solution of wave equation for this geometry will lead us to two solutions.

For transverse magnetic (TM) modes, the wave equation and the boundary conditions are.

$$\frac{\partial^2 H_y}{\partial z^2} + (k_0^2 \epsilon - \beta^2) H_y = 0 \quad (2.1)$$

$$E_x = -i \frac{1}{\omega \epsilon_0 \epsilon} \frac{\partial H_y}{\partial z} \quad (2.2)$$

$$E_z = -\frac{\beta}{\omega \epsilon_0 \epsilon} H_y$$

Solving the wave Eq. (2.1) with the boundary conditions as mentioned in Eq. (2.2), we arrive at following solutions.

$$H_y(z) = A_2 e^{i\beta x} e^{-k_z z}, \quad (2.3a)$$

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$$E_x(z) = iA_2 \frac{1}{\omega \varepsilon_0 \varepsilon_2} k_2 e^{i\beta x} e^{-k_2 z}, \quad (2.3b)$$

$$E_z(z) = -A_1 \frac{\beta}{\omega \varepsilon_0 \varepsilon_2} k_2 e^{i\beta x} e^{-k_2 z}, \quad (2.3c)$$

for $z > 0$, and

$$H_y(z) = A_1 e^{i\beta x} e^{k_1 z}, \quad (2.4a)$$

$$E_x(z) = -iA_1 \frac{1}{\omega \varepsilon_0 \varepsilon_1} k_1 e^{i\beta x} e^{k_1 z}, \quad (2.4b)$$

$$E_z(z) = -A_1 \frac{\beta}{\omega \varepsilon_0 \varepsilon_1} e^{i\beta x} e^{k_1 z}, \quad (2.4c)$$

for $z < 0$.

Here, β is the propagation constant in the direction of propagation and k_i is the component of wave vector perpendicular to the interface in two media. Its reciprocal gives us the evanescent decay length of field in the perpendicular direction to the interface. Using the boundary condition of field continuity, we arrive at following dispersion relation.

$$\beta = k_0 \sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}} \quad (2.5)$$

where ε_1 and ε_2 are the permittivity of the two layers. The above equation holds even for complex value of ε_1 . One can solve the wave equation similarly for transverse

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electric (TE) mode but it can be shown easily that these modes do not satisfy the condition of $\text{Re}[k_1] > 0$ and $\text{Re}[k_2] > 0$ except for the trivial solution. Hence it is concluded that SPs are only TM in nature, which means the electric field is perpendicular to the metal surface.

From the dispersion relation, it shows that the frequency dependent permittivity of metal ϵ_1 has to be of opposite sign to that of dielectric ϵ_2 , to make the square root bigger than one. If we choose a metal this condition is satisfied because the permittivity of metal is negative and complex.

Figure 2.3 Dispersion curve of SPs along with a photon in free space.

Consequently, exciting SPs will confront us with two properties of SPs: first the momentum mismatch between SPs and exciting photon [Figure 2.3] and secondly the electromagnetic field will decay exponential from the surface. As a result of this we need to use some special technique to excite SPs satisfying the momentum matching condition. Various techniques are used to excite SPs, some of them are using a prism and total internal reflection; the second one involves scattering from topographical hole on a thin film and third is to have a periodic corrugation on the metal surface like a grating. These techniques are basically to overcome the problem of momentum mismatch. Once the light has been coupled to the free electron of metal

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and converted into SPs, it will propagate along the flat metal surface but will gradually decay owing to the high absorption loss due to metals. The attenuation depends upon the dielectric property of the metal as a function of operating frequency. The reciprocal of imaginary part of the propagation constant gives us an estimate of propagation distance. For silver, which has comparatively less loss in visible region, the value is typically in the range of $10 - 100\mu\text{m}^{-1}$.

2.3 Applications of Surface Plasmon Polaritons

Many fundamental properties of SPPs have been studied and a lot of applications have been suggested including subwavelength optics^{2,3}, plasmonic integrated circuits^{29,30,31,32}, nano-lithography³³, magneto-optic data storage⁴, solar cells⁶, as well as light generation and microscopy⁵.

In the field of optics, one of the most attractive features of SPPs is the possibility to localize and guide light using subwavelength-sized structures. Many interesting findings and applications of SPPs in this direction have been reported by many groups^{1,34,35,36}. Recent progresses in the fabrication of nanostructures have paved ways of exploitation of various functional devices for future photonic circuits.

Waveguiding based on SPPs form a very interesting and important subject to discuss. In contrast to the conventional dielectric waveguide where light is guided by total internal reflection inside a core region with index higher than that of cladding region, in SPs based waveguides light is guided along the metal-dielectric interface owing to the negative dielectric constant of the metal side. This surface localization has led many researchers to explore the possibility waveguides based on SPPs with dimension much smaller than the wavelength that is propagated along it. Two

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important configurations of waveguides based on SPPs are Insulator-Metal-Insulator (IMI) and Metal-Insulator-Metal (MIM) waveguides³⁷.

IMI structure consists of two metal-dielectric surface which can support propagation of SPs. The SPs mode of one surface couples to other mode along the other surface provided the penetration depth of propagating mode inside the metal is less than the metal thickness. This is similar to coupling between two dielectric waveguide placed very close to each other. This leads to two guided modes and few leaky modes. When a thin metal layer is embedded inside a symmetric dielectric, the two modes traveling on the top and bottom interfaces are the same and they are coupled with each other to give rise to symmetric and asymmetric modes. These two modes have different spatial profile and as a result of that they show different behavior with decrease in the metal thickness. Symmetric mode, as evident from its name shows symmetric spatial distribution about the middle of the metal layer whereas the asymmetric mode is distributed asymmetrically. The IMI multilayer system, with its limited lateral confinement can be converted into two-dimensional SP waveguide. These structures have shown considerable application for guiding visible and infra-red frequencies. As in the case of infinite width waveguide there are significant differences between the symmetric and asymmetric environment. In the case of finite width waveguide, one of the fundamental modes shows low-loss behaviors with decreasing strip thickness and also is the only mode this is allowed below a critical strip thickness and width. This mode can show attenuation loss of the order of 10 – 0.1 dB/cm in telecommunication band, and exhibits a Gaussian profile for sufficiently thin films³⁸. First demonstration of this waveguide at 1.5 μm was reported by Berini *et. al.*³⁹. But these waveguides present considerable limitations as the mode profile is

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still two dimensional and the geometry of such waveguides is not small enough for sub-wavelength confinement. The mode confinement decreases significantly with decrease in the width of the strip. In order to provide truly subwavelength confinement, the thickness as well as the width of the waveguide has to be in subwavelength regime. This ultimate scaling of waveguides prompts to use metal nanowires as subwavelength guides ⁴⁰. The subwavelength confinement leads to propagation distance of the order of couple of microns which invites new research to increase the propagation distance.

Moving on to MIM structure, this geometry of subwavelength confinement consists of dielectric layer embedded between metal cladding. Here the electromagnetic wave is confined inside the subwavelength dielectric core via the coupling between the two modes traveling along the two surfaces in the direction perpendicular to the propagation direction. Laterally the physical extent of waveguide together with the increased wave vector of the surface plasmon mode propagating in the x direction will lead to better confinement. The coupled mode of the two interfaces will lead to two modes of which the odd mode will show a symmetric field distribution with the plane of symmetry. Large propagation constant can be achieved by adjusting the gap between the metal layers. MIM structures show potential of subwavelength integration with high density and better confinement. For example it has been shown that an Al based MIM structure operating at $1.5\ \mu\text{m}$ providing a propagation length of around $50\ \mu\text{m}$.

Fig 2.4(a) and 2.3(b) present a comparative study done by Rashid Zia *et. al.* between the two structures as discussed above ³⁷.

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Figure 2.4 (a) SPs propagation length and (b) spatial extent of the SPs modes as a function of centre layer thickness for IMI and MIM structure³⁷.

The above calculations were done for gold strip with air as insulator for the wavelength of 1.55 μm. Reflection Pole method (RPM) can be used to calculate the effective propagation constant (n_{eff}) for these structures. Details of this method are furnished in appendix A. For large thickness of central layer, it is seen that the structure tend to single interface propagation characteristics [Figure 2.4 (a)]. This is quite reasonable, when the thickness d increases; the two plasmon modes decouple with each other and travel independently. With decrease in the thickness of the central layer, the two separate mode start to interact. As a result, the propagation length of IMI structure increases whereas it decreases for MIM structure. For IMI structure the propagation distance seems to reach up to centimeter. This is because the SPPs are almost traveling in the air with very less penetration inside the metal layer which is the main cause of propagation loss.

The MIM modes exhibit a continuous decrease in the propagation length as the center insulating layer thickness is reduced. However, Figure 2.4(b) shows that by decreasing the dielectric layer thickness it is possible to realize deep subwavelength confinement without running into the problem of cut-off. As an example, it is shown

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that the spatial extent decreases to 100 nm for the metal to metal spacing of 50nm. It is thus possible to transport information in deep subwavelength size for a length of 1 μm . This is impossible with conventional dielectric waveguides.

Another interesting idea of using plasmonics as an enhancement mechanism for light sources was first recognized in beginning of 1980s⁴¹. In 2004, it was demonstrated that coating the surface of Gallium Nitride with plasmonics nanoparticles can enhance the intensity of emitted light by 14-fold⁴².

A concept of SPASER, in which the amplified SPPs are confined in a region with subwavelength distance away from the metal surface, was proposed by Bergman and Stockman¹³. The SPPs supported inside the SPASER are confined inside a region with subwavelength distance from the metal surface. SPASER is not like a conventional laser, it is a two-level emitter and it doesn't emit light waves but rather go radiationless transition where its excitation energy is transformed into quasistatic electric field energy of SPP. In a more recent report, SPASER-based nanolaser with a very small device dimension was reported⁴³. Nevertheless, the amplified SPPs supported inside the proposed SPASER was limited to dark modes and emit no photons. Recently, a two-dimensional SPASER array, which uses an asymmetric ring configuration to excite bright modes, was proposed to achieve lasing emission from both surfaces of the array⁴⁴. Another very different design of plasmonic based nanolaser was presented by Oulton and co-workers. In this design, a single hybrid surface-plasmon cavity-waveguide structure which consists of high-gain Cadmium Sulphide semiconductor nanowire separated from a flat silver surface by a 5-nm insulating gap⁴⁵. Their experiments and simulations show that the dimension of cavity and the spot size of the laser is about 25 nm, around 20 times smaller than the laser

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wavelength. The laser spot size can be controlled by the gap between nanowire and metal layer. They also show that there is no cut-off size for the laser to operate expecting that the dimension can further be reduced.

2.3.1 Plasmonic Light Source

One of the most promising applications of SPPs is surface bound electromagnetic waves supported by metals. From application point of view, there is an interest in generating high intensity, localized coherent field at very small dimensions. This performance is limited by high propagation loss because of metal. The solution to this loss problem, which has been proposed over the years in a number of publications^{46,47,48}, is to add an optical gain medium along with the metal layer. This concept of using gain medium, received attention as early as 1979 by Poltz *et al*⁴⁹. They considered gain enhanced total internal reflection (TIR) in presence of metal film, where the gain medium enhance the free space TIR wave through the mediation of excited SPPs on the metal surface. They also estimated the gain value required for a reflection singularity to exist in any thickness of metal. Later Sudarkin and Demkovich⁵⁰ studied the propagation of SPPs in the boundary of metal and a gain medium for transversally bounded and unbounded excitation laser beams. They also mention the possibility of creating a surface plasmon based laser. Mazair *et al*⁵¹ carried forward the analysis by considering it from guided wave standpoint, by investigating gain-assisted propagation of SPPs on the planar metal waveguides for different waveguide geometries. Their analysis in various geometries shows that the gain medium assists the SPP propagation by compensating for metal loss, making it possible for SPP to travel with little or no loss at the metal boundary and waveguides. In a very recent study of SPP propagation in a metal-insulator-metal plasmonic waveguide with

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semiconductor layer having very high value of optical gain, it was shown that near SPP resonance, the imaginary part of SPP propagation wave vector changes from positive to highly negative corresponding to amplified SPP propagation⁵². They observed that SPP mode experiences an unexpected gain of about 1000 times more than that expected in excited semiconductor. They attributed this unusual phenomenon to slowing down of average energy propagation in the structure. They identified this dramatic slowing down of energy velocity to as low as 200 m/s.

The first experimental demonstration of amplification of surface plasmons at the interface between silver film and a liquid containing organic dye was done by Seidel *et al*⁴⁶. The configuration of experiment was as shown in figure 2.5 below.

Figure 2.5 Twin ATR methods for SP amplification. Dye molecules, which are optically excited by the pump plasmon field, are made to coherently deliver their energy to the probe plasmon field by stimulated emission, thereby producing amplification. The spontaneous decay channel causes directional plasmon-coupled light emission visible as a light cone containing all colors of the dye emission spectrum. The inset shows a simplified energy level diagram of the dye molecules.⁴⁶

The optical pumping creates a population inversion in the dye molecule, which then acts to deliver energy to plasmon field by stimulated emission. The SP at the

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outer metal surface is excited if TM polarized light is incident from the glass side at a specific angle for which the projection of the k vector of the photon matches the k vector of the SP. At this angle, the reflectance as a function of incidence angle exhibits a dip whose width and depth depend on the degree of damping that the SP experiences. A reduction of the damping caused by the presence of an amplifying medium at the film surface will therefore result in a characteristic modification of reflectance curve providing a signature of stimulated emission of SPP.

Other experiment was also shown that using a gain layer adjacent to metal layer can compensate for the SPPs loss. Gain of about 420 cm^{-1} was proved to be sufficient to compensate about 30% of SPP loss in silver film⁴⁸. Another experimental proof of compensation of SPPs loss and stimulated emission of SPPs was reported by Noginov *et al*⁴⁷. In their experiment they observed stimulated emission of SPPs at optical frequency proving that compensation of SPP loss is indeed possible by using an adjacent gain medium. In their experiment, a silver film was coated on a glass prism and then it was covered with a dye doped polymer. Laser like emission of SPPs was observed as it decoupled to the glass prism in an attenuated total internal reflection setup. However the possibility of achieving coherent optical feedback to sustain lasing from such system was not explored. If a suitable feedback mechanism is accompanied, lasing can be achieved in such systems.

2.3.2 Plasmonic Modulator

Recent reports have demonstrated active plasmonic components that combine low optical loss with high mode confinement^{53,54}. Plasmonic modulator based on quantum dots¹⁵, ferroelectric material¹⁶, or liquid crystals¹⁷ have been proposed and demonstrated. In addition, SPP based modulators have also been realized using

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thermo-optic effect in the polymer cladding^{55,56}. One of the very useful active components based on SPPs can be Bragg grating. Bragg grating is very useful considering its broad range of application in distributed feedback and distributed Bragg reflection lasers, Bragg filters and modulators. SPP based Bragg grating is substantially different from the grating in dielectric waveguides due to that fact that former operates with SPP whereas latter operated with dielectric waveguide mode. From the well known attributes of SPPs, the modes supported in SPP based Bragg grating can only be TM and with high loss, but in the case of dielectric gratings, both TE and TM modes are supported. Dielectric grating modes have comparatively less loss but are larger in size. Plasmonic Bragg grating can be realized in both geometries of planar SPP waveguide; they are IMI and MIM structures. From the dispersion relation and either of these waveguides, it can be seen that the effective index of SPP mode supported in these structures are controlled by permittivity of metal and insulator layer as well as the width of central layer. It is possible to control the propagation of light by altering any of these parameters. Bragg grating is realized by periodically varying the width of central layer or alternatively by varying the index of central layer. For example, the insulator layer of MIM waveguide shown in figure 2.6, the effective index of SPP mode can be varied periodically which will eventually lead to Bragg reflection.

Figure 2.6 Schematic of SPP Bragg reflector. By periodically modulating the width of insulator layer slot in an MIM waveguide, Bragg reflection can be achieved.

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The concept of plasmonic Bragg grating comes from the experimental observation of photonic band gap (PBG) structures for SPPs⁵⁷. Conventional PBG structures are composed of regions of periodically varying refractive index that do not allow propagation of electromagnetic wave of certain wavelength range through them. Similarly, periodic scatterers for SPPs were designed to inhibit the propagation of SPPs in a certain range of wavelength. One of the earliest mention of grating structure was by D.L. Mills⁵⁸ in 1977. Later, Tredicucci *et al* used a periodic arrangement of Ti strips covered with an Au film to form a bi-metallic grating supporting SPPs at the top metal-insulator interface⁵⁹. Weeber *et al*⁶⁰, characterized a micro Bragg grating consisting of periodic arrangement of narrow slits engraved in Au strips evaporated onto an indium tin oxide doped glass substrate. Since these corrugated metal strips are based on IMI geometry, they do not provide necessary confinements needed for subwavelength photonic devices³⁷. This is because of much longer penetration depth of SPP field into dielectric medium compared to metallic layer. In addition the refractive index contrast between the effective index of two alternating layer is small, leading to smaller band gap for corrugated metal strips. Bragg reflectors can be realized by modulating either thickness⁶¹ or its index⁶² as well as periodically modulating both along the MIM waveguide. If one of the alternating indices in the insulator layer consists of an electro-optic material, a voltage controlled Bragg reflector can be designed. By applying an external voltage the refractive index of electro-optic layer can be changed and Bragg reflection can be altered making it an electro-optic modulator.

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Surface plasmonic lasing via the amplification of coupled surface plasmon waves inside insulator-metal-insulator waveguides: Design and analysis

This chapter proposes the structure for Plasmonic laser. Detailed theoretical analysis using finite-different time-domain (FDTD) technique and coupled-mode theory are performed in order to optimize the performance of the proposed IMI waveguide based lasing device. FDTD technique is used to find the optimized thickness of metal and dielectric layer. Furthermore, a coupled-mode theory is developed to analyze the lasing characteristics of proposed laser. Condition for single mode lasing is investigated.

3.1 Introduction

Propagation distance of SP waves, which is much shorter than that of the conventional dielectric optical waveguides, is limited by the high absorption loss of the metal film. Therefore, the use of optical gain is suggested to amplify the localized SP waves in nanostructures to achieve strong light localization effects⁴². In fact, the

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enhancement of localized SP waves at the interface of metallic thin films has been demonstrated experimentally by using dye solution as an optical gain medium^{46, 47}. On the other hand, the confinement characteristics of long-range SP waves on metallic waveguide adjacent to a gain medium were analyzed. It was estimated that the presence of optical gain with magnitude less than 400 cm^{-1} could realize lossless metallic waveguides⁵¹. However, the possibilities to realize coherent optical feedback to sustain lasing from the metallic waveguides are yet to be investigated.

In this chapter, the coupling behavior of propagating long-range SP waves between the two metal-dielectric interfaces of an insulator-metal-insulator (IMI) waveguide is analyzed by finite-difference time-domain (FDTD) technique. It can be shown that the SP waves are coupled together via the formation of supermodes (i.e., equivalent to directional coupling in the conventional waveguide directional couplers) within the IMI waveguides. Hence, the incorporation of gain medium onto one side of the dielectric layers is suggested to amplify the coupled SP waves. It is found that the absorption loss of the IMI waveguide is dependent on both the thickness of the metal film and gain region; however, the corresponding coupling coefficient is mainly affected by the thickness of metal film. Furthermore, a coupled-mode model is developed to study the lasing characteristics of IMI waveguides with coherent optical feedback. It is also proposed to realize grating along the cavity length on the dielectric layer opposite to the gain region so that single-mode plasmonic lasing can be achieved from the IMI waveguides.

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3.2 Surface Plasmonic Lasing: Theoretical Simulations

Coupling of SP waves between two metal-dielectric interfaces of an IMI waveguide, in which one of the dielectric layers is incorporated with optical gain, is proposed to realize plasmonic lasing. The propagation characteristics of the SP waves supported inside the IMI waveguides are studied by FDTD method. It is found that there are optimized thicknesses for the metal film and gain region to obtain minimum propagation loss. Furthermore, a coupled-mode model is developed to analyze the lasing characteristics of the IMI waveguides with coherent optical feedback. The conditions to achieve single-longitudinal-mode lasing from the IMI waveguides are also investigated.

3.2.1 Propagation characteristics of SP waves – FDTD analysis

The propagation characteristics of SP waves along the metal-dielectric interfaces of an IMI waveguide can be investigated by FDTD method. In the calculation, it is assumed that the thin film, which has thickness of 20 nm embedded inside a dielectric medium, is extended infinitely along the x and z directions where x -coordinate is the direction of propagation. In addition, the refractive indices of the dielectric medium and metal are assumed equal to be 1.54 and $0.0537+3.948i$ respectively. A free plane-wave with wavelength of ~ 594 nm is end-fired in the x -direction at the top dielectric layer at few tens of nanometers above the surface of the metal film (i.e., at $y > 15$ nm) and coupled to the SP waves on the top of the metal film.

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Figure 3.1 Instant distribution of $|H_z|^2$ intensity for the coupling SP waves propagating along the two metal interfaces of the IMI waveguide (a) without and (b) with gain at the bottom of the dielectric medium (at $y < 0$). The corresponding schematic diagrams of the IMI waveguides under end-fire coupling to the SP waves are also given.

Figure 3.1(a) shows the longitudinal propagation of SP waves with wavelength of ~ 594 nm inside an IMI waveguide. It is observed that the SP wave on the top dielectric layer coupled to the bottom dielectric layer and vice versa when the SP waves are moving along the x direction. It must be noted that the SP waves are excited only on one side of the metal-dielectric interface. Hence, this asymmetric excitation of SP waves along the y direction causes the coupling of SP waves between the two interfaces of the IMI waveguides. Furthermore, the asymmetric excitation causes the modal profile of SP waves differently to that of the eigenmodes excited symmetrically inside the IMI multilayer⁶³. The field intensity distribution given in Figure 3.1 is in fact the combination of symmetric and asymmetric SP waves. It is also observed that the SP waves completely disappeared at $x > 12 \mu\text{m}$. On the other hand, for the case given in Figure 3.1(b) where the bottom dielectric layer has an optical gain of $\sim 600 \text{ cm}^{-1}$, the SP waves can propagate much longer than that given in Figure 3.1(a). It must be noted that the real part of refractive indices of the top dielectric layer and bottom

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gain region are assumed to be the same. This indicates that the introduction of optical gain to the bottom dielectric layer can help to sustain the propagation of SP waves. This is because the extra optical gain compensates the propagation loss of the SP waves inside the dielectric layers.

It is noted that the propagation characteristics of SP waves in IMI waveguide are similar to the exchange of power between guided modes in a lossy directional coupler⁶⁴. Hence, it is necessary to study the equivalent propagation loss and coupling coefficient of the IMI waveguides. In addition, the lasing characteristics of SP waves can be studied by using coupled-mode theory if the corresponding propagation loss and coupling coefficient are known. From Figure 3.1, it is observed that the SP waves couple together through the presence of metal thin film. This implies that the corresponding propagation loss and coupling coefficient are dependent on the physical properties of the metal film. Furthermore, the thickness of gain medium determines the amplification efficiency of the SP waves. Hence, the dependence of propagation loss and coupling coefficient on the thickness of metal film and gain medium are required to be investigated.

Figure 3.2 Variation of (a) propagation loss, α , and (b) coupling coefficient, M , of the IMI waveguide with different thickness of metal film.

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Figure 3.2 shows the calculated values of propagation loss, α , and coupling coefficient, M , of the IMI waveguide versus the thickness of metal film, t_m . M is defined as the inverse of the distance between the two adjacent field intensity peaks along the propagation direction x , see also Fig 3.2(b). The parameter M reviews the efficiency of energy transfer between the two metal-dielectric interfaces when the SP waves propagating along the x direction. It is observed that the values of α and M increase with the reduction of t_m . This is because the electric field of asymmetric SP waves is strongly confined (i.e., more portion of electric field being interacted with the metal layer) inside metal layer with thinner thickness so that the value of α increases with the decrease of t_m . Furthermore, it is found that the propagation coefficient of the SP waves, β , remains unchanged at $16 \mu\text{m}^{-1}$ for various values of t_m .

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Figure 3.3 Variation of (a) propagation loss, α , and (b) coupling coefficient, M , of the IMI waveguide with different thickness of gain region, t_g .

Figure 3.3 shows the calculated values of α and M of the IMI waveguide versus the thickness of gain region, t_g . In the calculation, different values of t_m (40 to 60 nm) and imaginary refractive index of the gain region, n_{imag} , (-0.005 to -0.01 which correspond to the optical gain of ~ 260 to $\sim 510 \text{ cm}^{-1}$) were used. It is observed that the values of α reduced with t_g and saturated for t_g greater than 400 nm for most of the cases. On the other hand, the values of M are less dependent on the variation of t_g . It is

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noted that there is a minimum value of t_g to maximize the confinement of SP waves within the gain region. However, the values of M is less dependent on t_g as M is mainly determined by the thickness of the metal thin film as well as the refractive indices of the dielectric materials surrounding the metal thin film. From the above calculations, it is found that the optimized values of t_m and t_g are ~ 60 and ~ 400 nm respectively. This is because these values of parameters can obtain a small value of α for the SP waves as well as the dimensions of the dielectric waveguide can be minimized to subwavelength dimensions.

Figure 3.4 Plot of (a) propagation coefficient, α , and (b) coupling coefficient, M , of a waveguide with the variation of real part of refractive index of the gain region, n_{real} .

The real part of refractive index, n_{real} , of the host matrix (i.e., the dielectric layer with gain to be introduced) may vary due to the introduction of dopants and this may lead to the excitation of conventional waveguide modes. Hence, it is interesting to study the influence of small variation of n_{real} on the propagation characteristics of IMI waveguides. Figure 3.4 shows the variation of α and M with the small change of n_{real} . It is observed that a slight decrease of n_{real} reduces the propagation loss of the waveguides. This is because the reduction of refractive index reduces the confinement of SP waves at the dielectric-metal interface so that the SP waves experience less absorption loss from the metal. Hence, for the design of IMI waveguides, it is

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preferred that the gain medium has slightly less refractive index when compared to that of the cladding layer in order to achieve relatively low loss waveguide. However, if the different of n_{real} between gain region and cladding layer is larger than 0.01, this may lead to the excitation of conventional waveguide modes. As a result, the coupling of SP waves between the two dielectric-metal interfaces may not be supported.

3.2.2 Coupled-Mode Model for the IMI Waveguides

The physics of plasmonic lasing in IMI waveguide is investigated by assuming that the device consists of cladding layer, a thin layer of metal film, and an active layer on a bulk substrate. Coherent optical feedback is obtained from the facets with high reflection coating. This is possible as the SP waves are propagating in the direction perpendicular to the facets so that there is no interference of plasmonic effects with the optical reflection. The laser is optically pumped from the substrate by a high power light source. In addition, the cladding layer, metal layer, gain layer and substrate are made by SiO_2 , Ag, dye doped polymer, and bulk SiO_2 substrate respectively.

Figure 3.5 Transition stats in R6G dye doped polymer.

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In order to match the refractive index of SiO₂ as well as to obtain high optical gain under optical excitation, R6G doped polymethyl methacrylate (PMMA) active medium is selected to amplify ~594 nm stimulated emission under 532 nm light excitation^{48, 65}. Figure 3.5 shows a four-level model used to describe the recombination characteristics of R6G dye. The energy states on the left-hand-side of the figure represent a four-level system along with the triplet states on the right⁶⁶. The ground state is split into two vibronic levels with population distribution governed by Boltzmann distribution. In fact, it can be shown that the four-level model can be simplified to an equivalent two-level model⁶⁷. The detailed derivation of two-level model from four-level model is explained in appendix B. This approximation is possible as the non-radiative decay rate of populations at the highest energy level is larger than that of that the other energy levels and pumping rate. The simplified two-level model for R6G dye can be expressed as:

$$\frac{dN_2(x,t)}{dt} = [R_{13}(x,t) + \omega_a]N_1(x,t) - [\omega_e + \tau_{R2}^{-1}]N_2(x,t), \quad (3.1a)$$

$$N_1(x,t) + N_2(x,t) \cong N_{dye}(x,t), \quad (3.1b)$$

where, N_2 and N_1 are the populations at the upper and lower energy levels respectively of the two-level system. N_{dye} is the total dye concentration and τ_{R2} is the carrier lifetime. The polarization dependent pump absorption rates (R_{13}) and signal absorption (ω_a) and emission rates (ω_e) can be written by

$$R_{13}(x,t,\lambda_p) = A_{eff}^{-1} \frac{\sigma_p^{13}(\lambda_p)}{h\nu_p} P_{pump} \quad (3.2a)$$

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$$\omega_a(x, t, \lambda_s) = A_{\text{eff}}^{-1} \frac{\sigma_s^{12}(\lambda_s) P_s^0(\lambda_s)}{h \nu_s} S_A(x, t), \quad (3.2b)$$

$$\omega_e(x, t, \lambda_s) = A_{\text{eff}}^{-1} \frac{\sigma_s^{21}(\lambda_s) P_s^0(\lambda_s)}{h \nu_s} S_A(x, t), \quad (3.2c)$$

where h is Planck's constant, $\nu_{p(s)}$ is the frequency of pumped (signal) light, A_{eff} is the effective area, σ_p^{13} is the absorption cross section of the pump light and, σ_s^{12} and σ_s^{21} is the absorption and emission cross section of the signal light respectively. P_{pump} and $P_s^0(\lambda_s)$ is the pump and signal power respectively. λ_p (λ_s) is the pumped (signal) wavelength and S is the normalized signal power.

As shown in Figure 3.1, directional coupling of SP waves between the top and bottom dielectric layers of the IMI waveguides is observed. Therefore, the propagation characteristics of the SP waves, which have similarity to the guided modes in the directional coupler, can be studied by using coupled-mode theory. The normalized SP propagation waves, $S_{C(A)}^+$ and $S_{C(A)}^-$, which propagation characteristics are shown in Figure 3.6, can be described by a modified coupled-mode equations⁶⁴.

$$\left[\frac{1}{\nu_g} \frac{d}{dt} \pm \frac{d}{dx} \right] S_C^\pm = [-\alpha + j\delta\beta] S_C^\pm + jMS_A^\pm \quad (3.3a)$$

$$\left[\frac{1}{\nu_g} \frac{d}{dt} \pm \frac{d}{dx} \right] S_A^\pm = [(\Gamma g_s - \alpha) + j\delta\beta] S_A^\pm + jMS_C^\pm + \chi_A^\pm \quad (3.3b)$$

Where, $\delta\beta$ is the detuning from the propagation coefficient of the IMI waveguides, Γ is the confinement factor related to the confinement of SP waves inside the gain medium, and the signal optical gain, g_s , can be expressed as

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$$g_s = \sigma_s^{21} N_2 - \sigma_s^{12} N_1 \quad (3.4)$$

The parameters α and M have been defined in the above section. The normalized signal power in active layer, S_A , given in (3.2) is related to S_A^+ and S_A^- by

$$S_A = |S_A^+|^2 + |S_A^-|^2 \quad (3.5a)$$

It is also defined the normalized signal power in cladding layer as

$$S_C = |S_C^+|^2 + |S_C^-|^2 \quad (3.5b)$$

The boundary conditions for the lasers are given by

$$S_A^+(x=0, t) = r_L S_A^-(x=0, t) \quad \text{and} \quad S_A^-(x=L, t) = r_R S_A^+(x=L, t) \quad (3.6a)$$

$$S_C^+(x=0, t) = r_L S_C^-(x=0, t) \quad \text{and} \quad S_C^-(x=L, t) = r_R S_C^+(x=L, t) \quad (3.6b)$$

where r_L and r_R are the facets reflectivity at $x=0$ and $x=L$ respectively.

Figure 3.6 Schematic diagram of a SP laser with cladding layer, gain medium and substrate of same refractive index.

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In (3.3), χ_A^* is the spontaneous emission noise coupled to the signal fields. It is assumed that i) the distribution of spontaneous emission noise has a Gaussian profile and ii) the spontaneous emission fields coupled into the forward and reverse fields have the same magnitude. Hence, the spontaneous emission noise can be generated from a Gaussian distributed random number generator that satisfies the following correlation functions⁶⁸

$$\langle \chi_A(z, t) \chi_A^*(z', t') \rangle = P_{\text{spont}} \delta(z - z') \delta(t - t'), \quad (3.7a)$$

$$\langle \chi_A(z, t) \chi_A(z', t') \rangle = 0, \quad (3.7b)$$

where P_{spont} is the magnitude of the spontaneous emission power per area and is defined as

$$P_{\text{spont}} = \beta_s \nu_g \sigma_s^{21} \tau_{R2}^{-1} N_2, \quad (3.8)$$

where β_s ($=10^{-5}$) is the spontaneous coupling factor. Hence, by solving the rate equations of populations and coupled-mode equations of the SP waves self-consistently⁶⁸, the lasing characteristics of the IMI waveguides can be reviewed. This can be done by dividing the waveguide into discrete spatial sections of length Δx with temporal time steps taken as $\Delta t = \Delta x / \nu_g$, so that the optical field is sampled at the rate $f_s = 1/\Delta t$.

3.2.3 IMI Waveguide with Coated Facets

In this section, the steady state and transient response of the proposed dye doped IMI waveguides with coated facets are analyzed. In the calculation, it is

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assumed that the length of the waveguide, L is 300 μm and the facet coatings, r_L and r_R , both have equal reflectivity of 0.92 (i.e., Ag coated). In order to model the propagation characteristics of SP waves by using coupled mode equations, it is assumed that $\alpha = 500 \text{ cm}^{-1}$, $M = 0.2 \text{ cm}^{-1}$ and $\Gamma \sim 1$ as deduced from section 3.2.1 for the optimized dimensions (i.e., optimized values of t_m and t_g) of the IMI waveguides. The material parameters for the dye doped polymer are assumed ⁴⁸ to be $A_{\text{eff}} = 3 \times 10^{-11} \text{ m}^2$, $N_{\text{dye}} = 1.3 \times 10^{25} \text{ m}^{-3}$, $\sigma_p^{13} = 4.3 \times 10^{-20} \text{ m}^2$, $\sigma_s^{12} = 2.1 \times 10^{-20} \text{ m}^2$, $\sigma_s^{21} = 2.0 \times 10^{-20} \text{ m}^2$, and $\tau_{R2} = 3.0 \times 10^{-9} \text{ s}$. The refractive indices of SiO_2 and doped PMMA are assumed equal to 1.54.

In the calculation, the laser is divided into 600 ($= L/\Delta x$) equal length sections and the laser is switched on by the pump power with a step function

$$P_{\text{pump}}(t) = \begin{cases} 0 & t < 0 \\ P_{\text{ext}} & t \geq 0 \end{cases}, \quad (3.9)$$

where P_{ext} is the excitation power.

To study the modal behavior of IMI waveguides with facet reflection, the finite gain bandwidth of the dye solution should be taken into consideration. This can be accomplished by digitally filtering the SP waves ⁶⁹. Mode competition insures that only gain curvature around the central frequency is important. The frequency response of the filter, $H(\omega)$, used to model the optical gain profile can be expressed as

$$|H(\omega)|^2 = \frac{(1-b)^2}{1+b^2-2b \cos((\omega - \omega_p)\Delta t)}, \quad (3.10a)$$

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where $b \in (0,1)$ represents the filter width, ω_p is the frequency of the gain peak and Δt is the time step. The discrete implementation of this filter for the forward mode (and similarly for the reverse mode) is

$$S_A^+(t + \Delta t, x + \Delta x) = B \cdot S_A^+(t, x + \Delta x) + (1 - B) \cdot S_A^+(t, x), \quad (3.10b)$$

where $B = b \exp(j\omega_p \Delta t)$. A digital filter with $b = 0.009$ and $\Delta t = 20$ fs is used to approximate the optical gain of dye solution with bandwidth of ~ 3 THz.

Figure 3.7 Transient response of (a) S_A and S_C and (b) N_2 for IMI waveguide with coated facets $r_L = r_R = 0.92$ pumped at $P_{\text{ext}} = 1.03$ times threshold. (c) Steady-state lasing spectra of S_A for the facet coated IMI laser with P_{ext} equals to P_1 ($1.03 \times \text{threshold}$), P_2 ($2.0 \times \text{threshold}$) and P_3 ($3 \times \text{threshold}$).

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Figure 3.7 shows the transient response of the IMI waveguide under the excitation of P_{ext} equals to 1.03 times its threshold. It is observed that both S_A and S_C (N_2) exhibit in-phase (out-of-phase) relaxation oscillation. It is noted that mode beating of both S_A and S_C is due to the excitation of side modes. In addition, the formation of closely spaced Fabry Perot modes is the result of high facet reflectivity and long cavity length of the IMI waveguides.

The coupling behavior between S_A and S_C is explained in Figure 3.8 (a). It is clearly shown that S_A and S_C are varied out of phase along the laser cavity (i.e., energy transfers from active region to cladding region and vice versa), similar to the intensity distribution in Figure 3.1

Figure 3.8 (a) Plot of spatial distribution of S_A (black) and S_C (red). (b) Calculated steady-state lasing spectra without (top) and with (bottom) plasmonic coupling taken into consideration.

Figure 3.8 (b) shows the influence of plasmonic coupling on the resultant lasing spectra. It is noted that the mode spacing of Fabry Perot modes is about ~ 300 GHz without the influence of plasmonic coupling. However, the presence of

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plasmonic coupling, which is equivalent to the coupling of two Fabry Perot cavities together, induced extra modes in the emission spectrum.

3.2.4 IMI Waveguides with Periodic Grating

In order to suppress side modes, grating is introduced along the cladding layer of the IMI waveguides. Figure 3.9 shows the schematic diagram of the IMI waveguide with grating. It is assumed that the effective refractive index of cladding layer remains unchanged as the corresponding variation of refractive index inside the grating is in order of 10^{-3} .

Figure 3.9 Schematic diagram of a IMI waveguide with periodic grating.

If first order periodic grating is assumed to be fabricated at the cladding layer, the coupled-mode equations given in (3.3a) can be modified as

$$\left[\frac{1}{v_g} \frac{d}{dt} \pm \frac{d}{dx} \right] S_c^\pm = [-\alpha + j\delta\beta] S_c^\pm + jMS_A^\pm + j\kappa S_c^\mp \quad (3.11)$$

The coupling coefficient, κ , can be deduced from⁶⁹

$$\kappa \approx \frac{-\Delta n}{\lambda_s} \Gamma_s \sin\left(\frac{2\pi b}{\Lambda}\right) \quad (3.12)$$

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where Λ is the periodic of the grating, b is the lower index region of the grating, Δn is the refractive index different of the grating, and Γ_g is the confinement factor of the SP waves inside the grating. If the grating is realized by direct UV imprinting technique with $\Delta n \sim 5 \times 10^{-3}$ and $b/\Lambda \sim 0.75$, it can be shown that $\kappa \sim 80 \text{ cm}^{-1}$ for $\Gamma_g \sim 1$. It is possible to obtain $\Gamma_g \sim 1$ as the depth of the grating can match with the penetration depth of the SP waves inside the cladding layer provided that the depth of the grating is more than 200 nm.

Figure 3.10 Transient response of (a) S_A and S_C and (b) N_2 for the AR coating (i.e., $r_L = r_R = 0$) IMI waveguide with grating $\kappa = 80 \text{ cm}^{-1}$ and $P_{\text{ext}} = 1.03$ times its threshold.

Figure 3.10 shows the transient response of the IMI waveguide with $\kappa \sim 80 \text{ cm}^{-1}$ pumped at 1.03 times threshold. It is assumed that the cleaved facets are anti-reflection (AR) coated to avoid the formation of Fabry Perot modes. The transient response of the IMI waveguide with periodic grating is similar to that of the Fabry Perot cavities. However, mode beating is still observed in its transient response. Figure 3.11 shows the corresponding steady-state spatial distributions of S_A , S_C , N_2 as well as the lasing spectra of S_A at different P_{ext} . In Figure 3.11 (a) and (b), the spatial distributions of S_A and S_C at $P_{\text{ext}} = P_1$ are magnified by 5 times whereas that at $P_{\text{ext}} =$

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P_2 and P_3 are shifted up by 500 mW and 1000 mW respectively so that they can be easily read from the figures. It is observed that the mode beating is due to the excitation of two bandgap modes. This is expected as 1st order uniform grating will support bandgap modes⁷⁰.

Figure 3.11 Spatial distribution of (a) S_A , (b) S_C , (c) N_2 and (d) steady-state lasing spectra of S_A for the AR coated IMI laser with $\kappa = 80 \text{ cm}^{-1}$ and P_{ext} equals to P_1 ($1.03 \times \text{threshold}$), P_2 ($2.0 \times \text{threshold}$) and P_3 ($3 \times \text{threshold}$).

From the coupling wave theory, it is noted that the symmetry of the emission spectra can be broken if facet reflection is introduced into the consideration. Figure 3.12 repeats the investigation of grating coupled IMI waveguides with r_L and $r_R \sim 0.2$. The presence of small facet reflectivity breaks the symmetric of the periodic grating as well as excites bandgap mode. It is also observed that stable single-mode operation can be obtained even at higher pump intensities. Hence, it has shown that it is possibility to achieve single-mode lasing from IMI waveguides.

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Figure 3.12 Spatial distribution of (a) S_A , (b) S_C , (c) N_2 and (d) steady-state lasing spectra of S_A for the cleaved facets IMI laser with $\kappa = 80 \text{ cm}^{-1}$ and P_{ext} equals to P_1 ($1.03 \times \text{threshold}$), P_1 ($2.0 \times \text{threshold}$) and P_3 ($3 \times \text{threshold}$).

3.3 Discussions and Conclusions

Propagation characteristics of SP waves, with wavelength of $\sim 594 \text{ nm}$, along the IMI waveguides are studied by FDTD technique. It is observed that there is an exchange of power between the SP waves at the two Ag-SiO₂ interfaces due to the asymmetric excitation. The propagation characteristics of SP waves in the IMI waveguides are equivalent to that of the guided modes in the conventional directional couplers. It is found that the coupling characteristics of SP waves are dependent on the thickness of Ag film as well as the refractive index of dielectric layers. It is also observed that the IMI waveguides with the Ag thickness equal to $\sim 60 \text{ nm}$ can minimize the corresponding propagation loss to less than 500 cm^{-1} . However, if dielectric layers with higher refractive index are used for the design of IMI waveguides, coupling characteristics of SP waves will not be supported unless longer wavelength of SP waves is used. For example, for SP waves with wavelength of $\sim 1550 \text{ nm}$, materials such as InP or GaAs (i.e., refractive index of 3.4) can be used as the dielectric layers to realize coupling of SP waves.

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By introducing optical gain on one side of the dielectric layers, it can be shown that the amplification of SP waves can be obtained for the IMI waveguides. In addition, the thickness of the gain medium should be larger than 400 nm in order to confine the SP waves. It is proposed to use R6G doped PMMA as the dielectric layer with gain medium under the optical excitation of 532 nm light. This is because the refractive index of R6G doped PMMA is matched with the cladding layer of IMI waveguides. In addition, R6G dye can provide optical gain to more than 10^3 cm^{-1} at $\sim 600 \text{ nm}$ ^{46,47}. It must be noted that the refractive indices of the two dielectric layers should be close in order to allow effective coupling of SP waves. However, slightly reduction of refractive index in the gain medium can further enhance the amplification of the SP waves.

As it is not possible to simulate the roundtrip propagation characteristics of the SP waves by FDTD technique due to the requirement of extensive computational time, a coupled-mode model is developed to study the lasing characteristics of IMI waveguides. This is possible as the coupling characteristics of the two adjacent SP waves are similar to that of the guided modes inside the directional couplers. Hence, it is proposed to study the lasing characteristics of IMI waveguides with R6G doped polymer as the gain medium. In addition, the use of periodic grating along the cladding layer is suggested to realize single-mode lasing. It is found that single-mode lasing can be supported in 300 μm long IMI waveguides with cleaved facets provided that the corresponding value of κ is around 80 cm^{-1} in order to suppress the influence of facet reflection.

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An alternative and less demanding fabrication process to achieve lasing in the proposed IMI waveguide structure is to use a random feedback mechanism instead of grating.

Figure 3.13 Schematic diagram of a IMI waveguide with ZnO nanocrystals in the cladding layer.

The fabrication of grating can be complicated because of its small feature size. It is suggested that using nanoparticles of ZnO embedded in PMMA can form a good feedback layer and random lasing can be achieved. Index contrast between ZnO oxide and PMMA is large enough to achieve scattering of waves in the cladding layer. Fabrication details and optical characterization of this structure are discussed later in chapter 5.

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CHAPTER 4

Metal-insulator-metal waveguide Bragg reflector as a surface plasmon polaritons modulator

This chapter deals with an electro-optic modulator based on plasmonic Bragg reflector. The proposed device is based in a MIM plasmonic waveguide where the insulator layer consists of alternating dielectrics. Transfer matrix method is employed to design and optimize the transmission spectra of MIM waveguide Bragg reflector. Results are also verified by FDTD simulations. Furthermore, modulation response of the device is studied by applying an external alternating bias.

4.1 Introduction

Various functional SSP photonic devices (i.e., modulators and switches) based on thermal⁵³ or electro-optic⁷¹ effects have been demonstrated in recent past. However, these functional devices are sensitive to the operating wavelength due to the phase matching conditions of SPP waves. On the other hand, the use of MIM waveguide Bragg reflector, in which strong transverse confinement of SPP waves can be achieved,

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was proposed to control the emission wavelength of SPP devices ⁷². The Bragg reflector can be realized by either modulating its thickness ⁶¹ or index ⁶² as well as both ⁷³ periodically along the MIM waveguide so that a wide range of operating wavelength can be supported. Hence, if the functional SPP devices can be incorporated with MIM waveguide Bragg reflectors, the sensitivity to the operating wavelength can be minimized.

In this chapter, a voltage controlled MIM waveguide Bragg reflector is proposed as a SPP electro-optic modulator. The insulator layers of the Bragg reflector can be formed by periodic allocation of two dielectric materials along the longitudinal direction of the waveguide. KNbO_3 is used as one of the dielectric materials so that the corresponding refractive index can be changed under external bias. ZnS is chosen as the other dielectric material to match the refractive index of KNbO_3 at the off-state. Hence, when a bias is applied to the MIM waveguide, the increase in index contrast between the two dielectric materials induces Bragg reflection over a range of operating wavelength. Optical characteristics of MIM waveguide Bragg reflectors are investigated theoretically. Furthermore, the corresponding modulation response is studied under the bias of an AC sinusoidal voltage. It can be shown that the SPP electro-optic modulator with less sensitivity to the operating wavelength can be realized by the proposed MIM waveguide Bragg reflector.

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4.2 MIM waveguide Bragg reflector

Figure 4.1 Schematic of plasmonic Bragg reflector with alternating layers of n_1 and n_2 between two layers of silver (Ag).

Figure 4.1 shows the schematic of MIM SPP waveguide to be considered in our analysis. The waveguide, which is assumed to have an infinite length along the y direction, consists of an insulator layer sandwiched between two semi-infinite Ag layers. The insulator layer consists of alternating layers of KNbO₃ and ZnS which have lengths of w_1 and w_2 and thicknesses of d_1 and d_2 respectively. KNbO₃ is a promising electro-optic material due to its large electro-optic coefficients and high dielectric breakdown voltage⁷⁴. Furthermore, ZnS is selected as its refractive index can be close to that of KNbO₃ at off-state so that the confined SPP waves can propagate freely along the insulator layer. For the MIM waveguide under external bias, the SPP waves will experience Bragg reflection due to the periodic variation of refractive indices along the insulator layer. As a result, intensity modulation of SPP waves can be realized.

In general, the electro-optic properties of any electro-optic dielectric under external bias can be modeled by an index ellipsoid in rectangular coordinate as given below:

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$$\frac{x^2}{n_{11}^2} + \frac{y^2}{n_{22}^2} + \frac{z^2}{n_{33}^2} + \frac{2}{n_{23}^2} y \cdot z + \frac{2}{n_{13}^2} x \cdot z + \frac{2}{n_{12}^2} x \cdot y = 1 \quad (4.1)$$

where n_{ij} 's are refractive indices in respective directions. Under the influence of electric field, $\mathbf{E}(=E_x\mathbf{i}+E_y\mathbf{j}+E_z\mathbf{k})$, the refractive indices can be expressed as

$$\begin{aligned} \frac{1}{n_{11}^2} &= \frac{1}{n_x^2} + \gamma_{11}E_x + \gamma_{12}E_y + \gamma_{13}E_z, \quad \frac{1}{n_{23}^2} = \gamma_{41}E_x + \gamma_{42}E_y + \gamma_{43}E_z \\ \frac{1}{n_{22}^2} &= \frac{1}{n_y^2} + \gamma_{21}E_x + \gamma_{22}E_y + \gamma_{23}E_z, \quad \frac{1}{n_{13}^2} = \gamma_{51}E_x + \gamma_{52}E_y + \gamma_{53}E_z \\ \frac{1}{n_{33}^2} &= \frac{1}{n_z^2} + \gamma_{31}E_x + \gamma_{32}E_y + \gamma_{33}E_z, \quad \frac{1}{n_{12}^2} = \gamma_{61}E_x + \gamma_{62}E_y + \gamma_{63}E_z \end{aligned} \quad (4.2)$$

where n_x , n_y , and n_z are refractive indices in x , y and z directions respectively under zero bias. For KNbO_3 , γ_{13} , γ_{23} , γ_{33} , γ_{42} and γ_{51} are the only non-zero electro-optic coefficients⁷⁵. If bias voltage is applied along the z direction (i.e., $E_z \neq 0$, and $E_x = E_y = 0$), the ellipsoid equation can be simplified to

$$\left(\frac{1}{n_x^2} + \gamma_{13}E_z \right) x^2 + \left(\frac{1}{n_y^2} + \gamma_{23}E_z \right) y^2 + \left(\frac{1}{n_z^2} + \gamma_{33}E_z \right) z^2 = 1 \quad (4.3)$$

Hence, the refractive indices of KNbO_3 in 3 orthogonal directions (i.e., x , y , and z) under the influence of electric field can be expressed as:

$$n'_x = \left(n_x^{-2} + \gamma_{13}E_z \right)^{-1/2}, \quad n'_y = \left(n_y^{-2} + \gamma_{23}E_z \right)^{-1/2} \quad \text{and} \quad n'_z = \left(n_z^{-2} + \gamma_{33}E_z \right)^{-1/2} \quad (4.4)$$

where $\gamma_{13}=28$ pm/V, $\gamma_{23}=1.3$ pm/V, and $\gamma_{33}=64$ pm/V⁷⁵. The dependence on the operating wavelength of the parameters given in (4.4) can be estimated from the Sellmeier equation for KNbO_3 ⁷⁶.

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The effective refractive index of MIM waveguide supporting SPP waves can be deduced by the following wave equation:

$$\frac{\partial^2 H_y}{\partial z^2} + \left(k_0^2 \epsilon_x - \beta^2 \frac{\epsilon_x}{\epsilon_z} \right) H_y = 0 \quad (4.5)$$

where k_0 ($=2\pi/\lambda$) is the wave vector in free space, λ is the free space wavelength, and β is the effective propagation coefficient. ϵ_x and ϵ_z are the permittivities of the insulator layer in x and z directions respectively. The propagation coefficient in z direction, k , can be written as

$$k = \sqrt{k_0^2 \epsilon_x - \beta^2 \epsilon_x / \epsilon_z} . \quad (4.6)$$

Hence, n_{eff} of the MIM waveguide with defined thickness of either KNbO_3 or ZnS as the insulator can be deduced. Furthermore, using n_{eff} of the MIM waveguide, the reflectivity of the MIM waveguide Bragg reflector can be calculated by transfer matrix method (TMM) provided that the corresponding size (i.e., values of w_1 and w_2) and number of period are given in the investigation⁷⁷.

4.3 Calculation Results

In this section, the procedures to calculate the optimized dimensions of the MIM waveguide Bragg reflector are described. Firstly, effective index method developed in the above section is used to deduce the effective refractive index, n_{eff} , of the MIM waveguides. Based on the requirement that i) the difference between the $\text{Re}(n_{\text{eff}})$ of the biased $\text{Ag-KNbO}_3\text{-Ag}$ and Ag-ZnS-Ag waveguides is large enough to reflect SPP waves and ii) the value of $\text{Imag}(n_{\text{eff}})$ of the MIM waveguides is low enough to avoid absorption of SPP waves, the values of d_1 and d_2 can be estimated.

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Transfer matrix method will then be applied to calculate the transmission and reflection spectra of a MIM waveguide Bragg reflector using n_{eff} deduced from the selected values of d_1 and d_2 . The values of w_1 and w_2 are chosen for the Bragg condition to be occurred at $1.5 \mu\text{m}$. Finally, the values of d_1 , d_2 , w_1 , and w_2 are allowed to change in order to optimize the corresponding transmission and reflection spectra. In the following paragraphs, detailed optimization procedures for the MIM waveguide Bragg reflector will be explained.

Figure 4.2 Plot of n_{eff} versus wavelength of MIM waveguide with different thickness of KNbO_3 as the insulator and Ag as the metal layers. (a) Difference of $\text{Re}(n_{\text{eff}})$ between the on- and off- state of the MIM waveguide. (b) $\text{Im}(n_{\text{eff}})$ part of off- state and (c) $\text{Im}(n_{\text{eff}})$ part of on-state.

The value of n_{eff} of a MIM waveguide with KNbO_3 and Ag as the insulator and metal layers respectively are calculated under the influence of bias voltage, V_b . Figure 4.2(a) shows the difference of $\text{Re}(n_{\text{eff}})$ versus wavelength between the on- (i.e., $V_b = 65 \text{ V}$) and off- (i.e., $V_b = -65 \text{ V}$) states of the MIM waveguide. The thickness of the insulator layer, d_1 , is allowed to vary from 100 to 700 nm with a step of 100 nm during the calculation. This is because this range of d_1 is possible to be fabricated by the available deposition technique⁷⁸. Figures 4.2 (b) and (c) show the corresponding $\text{Im}(n_{\text{eff}})$ (i.e., absorption loss of the MIM waveguide) versus wavelength for the cases

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of off- and on- state respectively. It is observed that the difference of $\text{Re}(n_{\text{eff}})$ between on- and off- state as well as the values of $\text{Im}(n_{\text{eff}})$ for both states decrease with the increase of KNbO_3 thickness for all the wavelength. This is because the increase of d_1 decreases the amount of electric field experienced by KNbO_3 so that the difference in refractive index between the on- and off-state is reduced. Furthermore, the increase in d_1 reduces the confinement of SPP waves between the metal layers so that the corresponding absorption loss is also reduced.

It is noted that although small thickness of KNbO_3 can contribute to high reflectivity at Bragg wavelength, however, high absorption loss will also be experienced by SPP waves. Hence, there is a trade-off between large index contrast and low propagation loss of the SPP waves. $d_1 = 500 \text{ nm}$ is then chosen as the optimized thickness of KNbO_3 . This is because the corresponding index contrast and $\text{Im}(n_{\text{eff}})$ can be used to realize MIM waveguide Bragg reflector with low absorption loss and high reflectivity for the SPP waves. In this case, the value of n_{eff} for the Ag- KNbO_3 -Ag waveguide during off- and on- states is found to be $2.369+0.0016i$ and $2.333+0.00158i$ respectively. Taking the refractive index of bulk ZnS as 2.27 at operating wavelength of $1.5 \mu\text{m}$, the value of n_{eff} for Ag-ZnS-Ag waveguide is equal to $2.357+0.00156i$ for a thickness $d_2=500 \text{ nm}$.

The required values of w_1 and w_2 for the MIM waveguide Bragg reflector to operate at Bragg wavelength, λ_B , at $1.5 \mu\text{m}$ can be deduced from the Bragg condition $w_1\text{Re}(n_{\text{eff},1}) + w_2\text{Re}(n_{\text{eff},2}) = \lambda_B/2$, where $n_{\text{eff},1}$ and $n_{\text{eff},2}$ are the effective refractive indices of the MIM waveguide with KNbO_3 at on-state and ZnS as the insulator layer respectively. It can be shown that the $w_1 = 161 \text{ nm}$ and $w_2 = 159 \text{ nm}$ are the possible

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values to achieve peak reflection at λ_B equal to 1.5 μm . The difference between w_1 and w_2 is small because their corresponding difference in $\text{Re}(n_{\text{eff}})$ is only 1.5%.

Figure 4.3 (a) Reflection, (b) transmission and (c) absorption spectra of Bragg reflector for on- (solid black line) and off- state (dashed green line). (d) $\text{Re}(n_{\text{eff}})$ of on- and off- state (solid red and dashed blue respectively) and of n_2 (dotted black).

Figure 4.3 shows the reflection, transmission and absorption spectra of MIM waveguide Bragg reflector calculated by TMM. In the analysis, the number of period is set to 120. It is observed that the MIM waveguide can provide strong reflection at 1.5 μm for the on- state. However, non-uniform bandgap reflection is observed at the off-state of the MIM waveguide due to small difference in $\text{Re}(n_{\text{eff}})$ between ZnS and KNbO_3 at the off-state. In order to avoid the fluctuation of reflection over the bandgap wavelength, it is necessary to vary both d_1 and d_2 (i.e., to obtain one more degree of freedoms for the optimization process) to compensate the mismatch of refractive indices between ZnS and KNbO_3 at the off-state. In this case, the selection of both d_1 and d_2 should lead to: 1) the maximization of the difference of peak reflectivity between the on- and off- state, 2) the minimization of Bragg reflection (as close to

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zero as possible) at the off-state and 3) the minimization of absorption losses of the Bragg reflector at both the on- and off-state at the operating wavelength of $\lambda_B = 1.5 \mu\text{m}$.

Figure 4.4 Variation of (a) difference between peak reflection value of on- and off- state (b) difference between $\text{Re}(n_{\text{eff}})$ of off- state and n_2 . (c) absorption loss for off- state (d) absorption loss for on- state.

From Figure 4.4, it is noted that the optimized values of d_1 and d_2 , which satisfy the above 3 requirements, are found to be about 640 and 555 nm (indicated by circle in the figures) respectively.

In the calculation, it is noted that $\text{Re}(n_{\text{eff}})$ of KNbO_3 at the off-state as well as that of ZnS are found to be 2.348. In addition, under the Bragg condition, the values of w_1 and w_2 are re-calculated to be 162 nm and 160 nm respectively. Table 4.1 lists all the important parameters for the optimized dimensions of the MIM waveguide Bragg reflector. Reflection Pole Method (RPM) has been employed to solve for the propagation constants (n_{eff}).

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Table 4.1. Effective propagation constants for the selected parameters of MIM waveguide at 1.5 μm .

MIM waveguide	d_1/d_2	$\text{Re}(n_{\text{eff}})$	$\text{Im}(n_{\text{eff}})$	Loss $k_0\text{Im}(n_{\text{eff}})$	w_1/w_2
Ag-KNbO ₃ -Ag ($V_b = -65$ V)	$d_1 = 640$ nm	2.348	0.00139	58.22 cm^{-1}	$w_1 = 162$ nm
Ag-KNbO ₃ -Ag ($V_b = 65$ V)	$d_1 = 640$ nm	2.313	0.00135	56.55 cm^{-1}	$w_1 = 162$ nm
Ag-ZnS-Ag	$d_2 = 555$ nm	2.349	0.00149	62.41 cm^{-1}	$w_2 = 160$ nm

Figure 4.5 (a) Reflection, (b) transmission and (c) Absorption spectra of Bragg reflector for on- (solid black line) and off- (dashed green line) states. (d) $\text{Re}(n_{\text{eff}})$ of on- and off- state (solid red and dashed blue respectively) and of n_2 (dotted black).

Figure 4.5 plots the reflection, transmission and absorption spectra for the MIM waveguide with the optimized values of d_1 and d_2 and number of periods is set to

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120. It is observed that the reflection, transmission and absorption spectra for the on- and off- state are very distinct over the Bragg regime. In addition, the values of absorption loss for the on- and off-state of the waveguide are 23% and 40% respectively. Figure 4.5 (d) shows the values of $\text{Re}(n_{\text{eff}})$ for KNbO_3 and ZnS over the wavelength range. As their values are very close to each others, no strong reflection is observed at the off-state of the device.

Figure 4.6 Intensity distribution ($|H_y|^2$) with position at different wavelengths. Left side is for on- state while right side is for off- state. (a) and (c) at $\lambda=1.45 \mu\text{m}$, and (b) and (d) at $\lambda=1.5 \mu\text{m}$.

In order to verify the results obtained by TMM, FDTD simulations were also performed for the above optimized structure. As the MIM waveguide has total length of about $38 \mu\text{m}$ (i.e., 120 periods), the traveling distance of the SPP waves is also set to $38 \mu\text{m}$ in the FDTD simulator. Figure 4.6 plots the intensity distribution ($|H_y|^2$) of the SPP waves at different wavelength for both on-and off- state. It is observed in Figure 4.6 (b) that for the MIM waveguide at the on-state, the propagation of SPP waves is completely suppressed at $\lambda= 1.5 \mu\text{m}$. However, the SPP waves can be free to travel without much attenuation at the off-state of the device, see Figure 4.6 (d). In fact, similar characteristics of the MIM waveguide are observed for the SPP waves with wavelength in the Bragg regime as shown in Figure 4.5 (a). On the other hand, SPP waves with wavelengths away from the Bragg regime have shown no attenuation

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inside the MIM waveguide either at the on- or off- state as seen in Figure 4.6 (a) and (c).

The small-signal modulation response of the MIM waveguide operating at $1.5\ \mu\text{m}$ is also investigated. It is assumed that the device is modulated by an AC sinusoidal voltage with peak-to-peak voltage of 130 V (i.e., $\pm 65\ \text{V}$). The area of the MIM waveguide is set to $10 \times 40\ \mu\text{m}^2$ with average thickness of 615 nm. The capacitance of the MIM waveguides was estimated to be 0.03 pF by using parallel plate formula as the influence of fringe effect will introduce less than 15% of error in the calculation. If the thickness of Ag is few hundreds of nm (i.e., $> 300\ \text{nm}$), the total resistance of the MIM waveguide will be determined by the termination resistor, which usually has a value of about $50\ \Omega$, of the driving voltage source. Figure 4.7 (d) plots the reflectivity of the MIM waveguide operating at $1.5\ \mu\text{m}$ versus the normalized modulation frequency (i.e., normalized by the RC time constant of the MIM waveguide). In Figure 4.7 (b), the solid line represents the variation of $\text{Re}(n_{\text{eff}})$ versus time for the Ag-KNbO₃-Ag under the influence of the sinusoidal voltage as shown in Figure 4.7(a). The dashed line represents the effective refractive index of Ag-ZnS-Ag versus time. Figure 4.7 (c) plots the reflectivity versus time. The reflection peak (indicated by a dot in Figure 4.7 (c)) represents the solid line shown in Figure 4.7(d). It is seen that the peak reflectivity drops to 69% at -3dB point compared to 74% for steady state case.

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Figure 4.7 (a) sinusoidal bias voltage (b) variation of $\text{Re}(n_{\text{eff}})$ of KNbO₃ (solid red line) and $\text{Re}(n_{\text{eff}})$ of ZnS (dotted black line) (c) variation of resultant Bragg reflection (d) variation of peak reflectivity with normalized modulation frequency.

4.4 Discussions and Conclusions

The electro-optic properties of KNbO₃ have been exploited to control the reflectivity of a MIM waveguide Bragg reflector. The insulator layer of the MIM waveguide is constructed by periodic variation of two dielectric materials (i.e., KNbO₃ and ZnS) over the length of the waveguide. In order to optimize the performance of the MIM waveguide, it is allowed to vary d_1 and d_2 so that the difference of peak reflectivity between the on- and off-state as well as the corresponding propagation loss can be optimized simultaneously. The value of external bias was chosen so that its value is well within the breakdown limit of insulator layer. It should also be noted that the insulator layer is asymmetric with respect to centre of the waveguides unlike other Bragg reflectors proposed earlier⁷². Calculations show that there is no significant change in the performance of the device because of asymmetric arrangement of insulator layer.

Furthermore, the design of MIM waveguide Bragg reflectors allows the fabrication of SPP electro-optic modulator to be realistic. In fact, the MIM waveguide

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can be fabricated by the electron beam lithographic technique similar to that proposed in ⁶¹. Firstly, an Ag layer is deposited onto a Si substrate to form the bottom metal layer of the MIM waveguides. Then, a layer of KNbO₃ is deposited onto the substrate followed by a layer of positive electron beam resist. A grating mask will then be formed on the resist via electron beam lithography technique. After the formation of grating mask, reactive ion etching will be performed to completely remove the uncovered KNbO₃ layer. ZnS will then be deposited onto the sample with thickness thinner than that of the KNbO₃ layer. After the deposition, the resist will be removed to give the desired pattern of the insulator layer. Finally, another Ag layer will be deposited onto the dielectric surface as the top metal layer of the MIM waveguide. Hence, it is possible to realize the proposed MIM waveguide Bragg reflector.

In conclusion, we have proposed a simple electro-optic SPP modulator based of voltage controlled plasmonic Bragg reflector. The reflectivity contrast between the on- and off- states can be larger than 65% for a central wavelength making it a promising SPP modulator. Moreover, other operating wavelength can also be selected by changing the width of alternating insulator layer. In addition, the corresponding propagation loss can be minimized to not more than 67 cm⁻¹ and a stable modulation response for the reflectivity of the MIM waveguide Bragg reflector can be predicted. This modulator is expected to have applications in integrated photonic circuits and SPP- based devices.

CHAPTER 5

Random laser action in insulator-metal-insulator surface plasmon waveguides

This chapter presents the experimental realization of plasmonic laser discussed in chapter 3. IMI plasmonic waveguide, in which the top and bottom dielectric layers are incorporated with scatters and optical gain respectively, was realized to support random lasing action. The fabrication process is discussed. Photoluminescence results show that under the optical excitation of 532nm, sharp peaks around 590 nm were observed from the edge of the top dielectric. Dependence of lasing threshold on excitation area is also measured to confirm random lasing.

5.1 Introduction

As discussed in chapter 3, incorporating a gain medium along with the metal layer can provide necessary gain to compensate for the propagation loss of SPP and this idea can be further extended to realize a SPP based lasing device. Stimulated emission of SP waves has been recently demonstrated by using a dye-doped polymer as the gain medium to compensate the absorption loss at the metal-dielectric interface

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of the SP waveguides ⁴⁷. However, lasing emission of SP waves (i.e., stimulated emission of coherent SP waves) has not been achieved due to the lack of optical feedback. In this chapter, optical gain and feedback mechanism are introduced into the IMI SP waveguide to realize random lasing action for the SP waves. Experimental results presented in this chapter prove that it is indeed possible to realize a SPP based laser as proposed earlier in chapter 3.

5.2 Device structure

Figure 5.1 shows a schematic of the proposed IMI waveguide supporting surface plasmon random lasing.

Fig 5.1 Schematic diagram of a IMI surface plasmonic waveguide.

The bottom dielectric layer of present IMI waveguide, which is composed of PMMA incorporated with R6G dye, provides optical gain to sustain amplification of the SP waves at around 590 nm. The use of PMMA is due to its refractive index is

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closed to that of the quartz substrate (i.e., with refractive index of about 1.55) and R6G can provide optical gain at around 590 nm. Due to the low optical absorption loss of Ag at 590 nm, it is used as the metal layer to guide the propagation of SP waves. The top dielectric layer, which consists of PMMA doped with ZnO nanocrystals (NCs) is used to achieve coherent optical feedback of SP waves. The choice of ZnO NCs is due to its low absorption loss at around 590 nm. The difference of refractive indices between ZnO NCs and PMMA is also large enough to provide strong optical scattering. It must be noted that the lasing light is mainly scattered in the direction parallel to the metal layer. This is because 1) thick ZnO NCs doped PMMA layer can cause the diffusion of scattered light and prevent from travelling to the surface and 2) the air-PMMA layer interface traps the scattered light within the top dielectric waveguide by total internal reflection. In addition, as the effective refractive index of top and bottom dielectric layers can be matched, SP waves will only be excited at the two metal-dielectric interfaces¹⁸. Therefore, it is expected that the proposed waveguide only supports SP waves scattering along the metal layer.

The IMI waveguide laser is optically pumped at 532 nm in the direction perpendicular to the quartz substrate and lasing emission is collected from the edge of the top dielectric layer. This arrangement is used due to the fact that the propagating SP waves, which are confined at the interface between the metal and bottom dielectric layer, are excited and amplified by the optical gain of the bottom dielectric layer. The propagating SP waves will then couple to the interface between the metal and top dielectric layer and experience strong optical scattering from the ZnO NCs. If the optical gain is large enough to overcome the scattering and absorption losses of the IMI waveguide as well as the ZnO NCs can provide coherent optical feedback,

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random lasing action of the SP waves can be observed from the edge of the top dielectric layer.

In order to minimize the waveguide loss, FDTD calculations were performed to optimize the thickness of metal and gain layers of the IMI waveguides. The details of optimization process is already discusses in detail in chapter 3. In the simulation, it was assumed that the two infinite thick dielectric layers have the same refractive index of 1.55, Ag is the metal layer sandwiched between the two dielectric layers and the SP waves have optical wavelength of 590 nm. The influence of scattering loss due to the presence of ZnO NCs was ignored in the calculation as it is less dependent on the geometry of the IMI waveguides.

Figure 5.2 Propagation loss of the SP waves versus the thickness of Ag and gain layers. t_m is the thickness of Ag.

Figure 5.2 presents the results obtained from the optimization process. It is observed that the propagation loss remains unchanged for the thickness of the metal layer larger than 50 nm. Therefore, the thickness of Ag of the IMI waveguide was selected to be around 50 nm thick. Furthermore, the optical gain of the IMI waveguide

is saturated for the bottom dielectric layer with thickness larger than 400 nm. In fact, it is preferred to have thick top and bottom dielectric layers in order to achieve strong confinement and amplification of SP waves at the metal-dielectric interfaces. This is because the SP waves confined at the dielectric-metal interfaces could leak to the top (bottom) dielectric layer, which has large difference in refractive index between PMMA and air (PMMA and quartz substrate), to form conventional index guiding modes if the thickness of the dielectric layers is shorter than the lasing wavelength. Hence, for the design of IMI waveguides, the top and bottom dielectric layers were chosen to be few micrometers thick.

5.3 Fabrication Process

For the fabrication of the bottom dielectric layer, a mixture of R6G dye and PMMA dissolved in dichloromethane was deposited on a quartz substrate by spin coating. The concentration of R6G dye in PMMA was selected to be 2.1×10^{-2} M and the thickness of spin coated film was set to about 8 μm . This thickness of bottom dielectric layer is sufficient to avoid leakage of SP waves to the substrate as well as to provide extra gain to facilitate lasing. Ag of thickness varying between 30 to 50 nm was deposited on the surface of the bottom dielectric layer by electron-beam evaporation. On the other hand, ZnO NCs with average size of 100 nm were mixed with PMMA in dichloromethane. The concentration of ZnO NCs mixture was calibrated to be 100 g/l. These size and concentration of the ZnO NCs mixture were selected as 1) the size of ZnO NCs is commercially available and 2) the mixture can provide strong scattering to form closed-loop paths of light. In fact, it can be shown that the scattering mean free path of the ZnO NCs mixture, which can be estimated by

the coherent backscattering experiment using a 635 nm pulsed laser diode as a probe light, is about 0.85 times the laser wavelength. This implies that the light can be returned to a scatterer from which it was scattered before and thereby forming closed loop paths. The ZnO NCs mixture was spin coated on to the surface of Ag layer and the thickness of the top dielectric layer was set to 8 μm . This thickness of top dielectric layer is large enough to 1) avoid leakage of SP waves and 2) trap the scattering of light. In addition, the IMI waveguides without ZnO NCs were fabricated to confirm that 1) the unintentional scatters presented in the polymeric films do not facilitate random lasing action ⁷⁹ as well as 2) the IMI waveguides support the propagation and amplification of SP waves.

5.4 Optical Characterization

The IMI waveguides were optically pumped at room temperature by a frequency-doubled Nd:YAG (yttrium aluminum garnet) laser (532 nm) at pulsed operation (120 ps, 10 Hz). Optical excitation was achieved by using a cylindrical lens to focus a $2 \times 10 \text{ mm}^2$ pump stripe onto the quartz substrate. Details of photoluminescence setup are furnished in appendix C. Edge emission from the top dielectric layer of the IMI waveguide was then collected through an objective lens. In addition, the bottom part of the IMI waveguide was covered to avoid the influence of amplified spontaneous radiation emitted from the bottom dielectric layer.

Figure 5.3 Spontaneous emission spectra versus different pump intensities of the IMI waveguide without ZnO NCs at the top dielectric layer. The pump intensity is increased (in the direction of the arrow) from 0.01 to 0.04 MW/mm².

Figure 5.3 shows the measured emission spectra versus different pumped intensities of an IMI waveguide without ZnO NCs and the corresponding Ag layer has a thickness of 50 nm. It is observed that the emission spectra have a broadened peak at around 590 nm. As expected, the observation of amplified spontaneous emission from the emission spectra is due to the amplification of SP waves when its travel along the metal layer. However, amplified spontaneous emission was not observed from the surface of the IMI waveguides. Hence, it is verified that the metal layer has mainly contributed to the guiding of SP waves inside the IMI waveguides. The propagating SP waves generated from the bottom dielectric layer can be coupled to the top dielectric layer. In addition, the surface roughness of the top dielectric layer is not sufficient to provide optical feedback.

Figure 5.4 Light-light curve and of the IMI waveguide with 50 nm thick of Ag under various pump intensities. The insert plots the lasing threshold versus the thickness of Ag.

The above experiment was repeated for the IMI waveguides with ZnO NCs inside the top dielectric layer. Figure 5.4 plots the light-light curve of the IMI waveguide with 50 nm thick Ag film. A kink (i.e., lasing threshold), which indicates that the IMI waveguide exhibits lasing emission, is observed from the figure. The insert of Figure 5.4 also shows the lasing threshold of IMI waveguides with different thickness of Ag layer. It is observed that the lasing threshold of the IMI waveguide increases with the decrease of Ag thickness. This is because the propagation loss of SP waves increases with the decrease of Ag thickness as predicted in chapter 3.

Fig 5.5 Spontaneous emission spectra versus different pump intensities of the IMI waveguide without ZnO NCs at the top dielectric layer. The pump intensity is increased (in the direction of the arrow) from 0.01 to 0.04 MW/mm². (b) far-field measured from the edge of the IMI waveguide under lasing operation.

Figure 5.5(a) shows the emission spectra of the IMI waveguide with 50 nm thick Ag film. Several peaks with linewidth less than 1 nm were observed near 590 nm at high pumping intensities. This is due to the strong optical scattering of the ZnO NCs inside the top dielectric layer so that closed-loop paths of light (i.e., lasing peaks) can be formed through the recurrent of scattering light. In addition, the number of lasing peaks increases with the increase of pumping intensity. This is one of the strong evidences of random lasing action. Figure 5.5(b) shows the far field profile measured from the edge of the IMI waveguide. It is observed that the lasing beam is collimated in the vertical direction so that the random lasing action should be supported by the SP waves propagating along the metal surface. The emission spectra and far field profiles of IMI waveguides with other thickness of Ag are similar to that of Figure 5.5 so that their plots are not repeated.

From the above measurement, one of the essential characteristics of random lasing action has been observed from the IMI waveguides. However, another essential

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characteristic of random lasing action, that is the lasing spectra observed from a random medium are different at different observation angle, has not been observed from the surface of the top dielectric layer. This is because the SP waves are strongly guided at the two metal-dielectric interfaces and the radiation of scattered light is suppressed by a thick layer of ZnO NCs doped PMMA. On the other hand, random laser theory has indicated that the plot of $A_{th}^{2/3}$ versus P_{th}^{-1} has a linear relationship, where A_{th} is threshold excitation area and P_{th} is lasing threshold observed from the edge of the IMI waveguides⁸⁰. Figure 5.6 shows the plot of $A_{th}^{2/3}$ against P_{th}^{-1} for the IMI waveguide with Ag thickness of 50 nm. A linear relationship between $A_{th}^{2/3}$ and P_{th}^{-1} is shown in Figure 5.6 implies that the SP waves exhibited random lasing action.

Figure 5.6 Plot of $A_{th}^{2/3}$ versus $1/P_{th}$ for the IMI waveguide with 50 nm thick Ag.

5.5 Conclusion and Discussion

In conclusion, random lasing action is demonstrated from an IMI waveguide with the top and bottom dielectric layers incorporated with scatters and optical gain respectively. Although the scatter and gain media are spatially separated, the SP waves can obtain scattering and optical amplification simultaneously to form closed-loop paths of light along the surface of the metal layer. This is because the strongly confined SP waves propagating at the interfaces of the two metal-dielectric interfaces are coupled together through the thin metal layer. As a result, sharp peaks of linewidth less than 1 nm are observed from the emission spectra and the number of sharp peaks increases with the increase of pump intensity. It should be noted that the metal layer has no contribution to the formation of random cavities as they are in orthogonal directions. Furthermore, the dependence of lasing threshold on the excitation area agrees with the random laser theory. Hence, we have verified that the proposed IMI waveguides can support random lasing action for the SP waves.

CHAPTER 6

A surface-emitting distributed-feedback plasmonic laser

This chapter presents an improved configuration of the plasmonic laser proposed in chapter 3 and experimentally realized in chapter 5. A surface-emitting distributed-feedback plasmonic laser is proposed. It consists of a gain layer, a metal grating layer to generate SPPs and provide feedback. Further, a decoupling layer is used to extract the localized SPs. The emission is only in one direction unlike the geometry proposed earlier in the thesis.

6.1 Introduction

As discussed earlier, introduction of a gain medium adjacent to the metal layer is one of the possible solutions to compensate the high absorption loss and if the optical gain is high enough to overwhelm the absorption loss, the compact plasmonic lasers may be realized^{81,82,83}. The lasing device presented in this chapter is similar to the concept of “SPASER”, in which the amplified SPPs are confined inside a region with a subwavelength distance away from the metal surface, first proposed by Bergman and Stockman¹³. Based on the same concept, a SPASER-based nanolaser with a very small device dimension was reported recently¹³. One important thing to note is that

the amplified SPPs supported inside the proposed SPASER are limited to dark modes – emit no photons. To overcome this limitation, a two-dimensional SPASER array, which uses an asymmetric ring configuration to excite bright modes, was recently proposed to achieve lasing emission from both surfaces of the array^{44,84}. However for these kinds of lasing devices, the two-dimensional SPASER array or multilayer based plasmonic lasers to be practical, lasing emission only from one side of the surface is more preferred.

It is noted that SPPs generated under the Kretschmann system are inherently leaky waves due to the decoupling effect from high-index prism layer^{26,47,85}. Therefore, it may be possible to extract localized SPPs by placing a high-index dielectric layer on the metal surface of the SPASER. In this chapter, we proposed a low-threshold surface-emitting distributed-feedback plasmonic laser (SE-DFB PL) with an asymmetric dielectric-air-metal-dielectric configuration. In this structure, SPPs supported at the air-silver interface are amplified by an active polymer medium adjacent to a silver grating, which is used to provide coherent optical feedback to the SPPs. To decouple the localized SPPs confined by the grating surface into the free space, a decoupling layer (DCL) with a relatively higher refractive index is used. It can be shown that there is an optimized design for the proposed SE-DFB PL. Efficient plasmonic lasing with a high quality factor can also be achieved.

6.2 Surface-Emitting Distributed-Feedback Plasmonic Laser

Fig 6.1 Schematic diagram of the proposed surface emitting distributed feedback plasmonic laser.

Schematic diagram of the proposed SE-DFB PL is shown in Figure 6.1. It is composed of (from bottom to top) a quartz substrate, an active region with PMMA (polymethy methacrylate) doped by R6G (rhodamine 6G), a one-dimensional silver grating, a spacer layer, and a high-index decoupling layer. Optical gain is obtained from the active layer by external pumping (at ~ 532 nm by using a frequency-double Nd:YAG laser) from the bottom of the transparent substrate. The real part of the refractive index of the active region [i.e., $\text{real}(n_A)$] is ~ 1.5 and its imaginary part is related to the amount of optical gain. The gain medium has a thickness of $d_A = 500$ nm. To realize the resonant interaction between the emission light from the gain medium and the SPPs supported by the air-silver interface, the grating period is taken to be

around 450 nm, which provides the constructive feedback for the light at ~ 600 nm (which is also the lasing peak of R6G material⁴⁷). The grating duty cycle (i.e., b/Λ) is initially selected to be 0.8 in order to obtain the strong feedback⁸⁶. The DCL (with thickness of 900 nm) should be close to the grating upper surface to “contact” spatially with the SPP fields so as to decouple the dark modes (i.e., stimulated SPP waves confined by the air-metal interface⁸⁷) into the bright modes for surface emitting action. In the following sections, the lasing performance and optimized dimensions of the SE-DFB PL will be analyzed by a FDTD simulation. In this study, a Lorentzian index profile, which is centered at 600 nm and characterized by the linewidth (~ 16 THz) and peak gain coefficient (g_{peak}), will be used for the active layer to fit the gain spectrum of R6G material.

6.3 Calculation Results

Figure 6.2 shows the calculated lasing spectra of the plasmonic laser without DCL under gain coefficients $g_{\text{peak}} = 440, 770, 938, 1050, \text{ and } 1100 \text{ cm}^{-1}$, respectively. This is intended to show the importance of DCL for the excitation of surface emission. In the calculation, $d_M = 40$ nm and $d_G = 20$ nm, and the spectra at the typical point with the maximal SPP intensity (see the inset of Figure 6.2) are recorded.

It is found that the lasing peaks occur at wavelength $\lambda \sim 605.2$ nm with spectrum linewidth ~ 1 nm. The lasing peak becomes very prominent when $g > 700 \text{ cm}^{-1}$, showing that the laser threshold is less than 700 cm^{-1} . This can be interpreted by the strong transverse modal characteristics of the SE-DFB PL. As the grating layer is surrounded by air, SPPs will experience strong optical confinement inside the gain region so that the corresponding laser threshold can be minimized.

Fig 6.2 lasing spectra of plasmonic laser without DCL under different gain coefficient. Inset show the SPP field intensity in xy plane.

The inset of Figure 6.2 displays the image of the SPP field intensity in xy plane (with $g = 1100 \text{ cm}^{-1}$). It is observed that the SPPs are strongly confined by the air-silver interface even at very strong intensity. In addition, the SPPs decay rapidly when entering the air region. As indicated in Ref. 87, the SPP modes generated from such a configuration are actually the dark modes and no photons will be emitted.

We repeat the calculation of Figure 6.2 by introducing a DCL (with refractive index $n_D = 1.5$) onto the plasmonic laser. The DCL is placed at $d_s = 40 \text{ nm}$ above the grating layer and air is used as the spacer layer. In this calculation, the gain coefficient of the active region is kept at 1100 cm^{-1} .

Fig 6.3 (a) field intensity and (b) lasing emission intensity for plasmonic laser with DCL layer at point O_1 and O_2 .

The simulation results are plotted in Figure 6.3, where (a) and (b) represent the field image in xy plane and lasing spectra at the locations ' O_1 ' and ' O_2 ', respectively. Due to the use of DCL, the central lasing wavelength is found to exhibit a slight blue shift of ~ 0.2 nm, accompanied by a decrease of lasing intensity (this is because the shift of transverse mode towards the DCL decreases the coupling of SPPs with gain medium). However, it is noted that the presence of DCL causes the localized SPPs to be decoupled from the grating layer to the high-index layer by the excitation of radiation waves [see Figure 6.3(a)]. This decoupling effect can be explained as follows. SPPs, which have a wave vector that is unreachable in the air region (i.e., phase mismatching), are strongly confined within the air-silver interface²⁶. When a high-index layer is placed near to the grating surface, there exists a wave vector matching with the SPPs (i.e., phase matching) due to the increase of wave vector in the y direction. As a result, the localized SPPs will then be decoupled from the metal surface and turn into the usual electromagnetic waves to form the surface emission. We must

indicate that the existence of spacer layer is necessary. This is because if we replace the spacer layer with the DCL the SPP vector will become unreachable in DCL. Moreover, as can be seen from Figure 6.3, the emission direction is along the vertical direction, forming a perfect surface-emitting laser.

6.4 Parameter Optimization

It is noted that the key parameters affecting the lasing performance of SE-DFB PLs are the thickness of metal film (d_M), thickness of metal grating (d_G), spacer layer thickness (d_S), refractive index of DCL (n_D), grating period (Λ), as well as the duty cycle of the grating (b/Λ). In the following paragraphs, these parameters will be optimized in the design of SE-DFB PLs. However, the value of Λ will be fixed at 450 nm in the optimization process to fit with the peak of R6G emission spectrum.

Fig 6.4 Variation of peak field intensity with (a) d_M and d_G (b) d_S (c) n_D , and (d) b/Λ ,

Figure 6.4 displays the variation of peak field intensity in DCL versus d_M , d_G , d_S , n_D , and b/Λ , which have the initial values of 40 nm, 20 nm, 40 nm, 1.5, and 0.8, respectively. In addition, the value of g was maintained at 1100 cm^{-1} and that of d_A was kept at 500 nm. It is observed from Figure 6.4(a) and (b) that the optimal values of d_M , d_G , and d_S are found to be 50, 60, and 70 nm, respectively. Furthermore, it is noted that the value of d_M plays a crucial role in the design of SE-DFB PLs. This is because the thickness of metal grating determines the absorption loss and the coupling efficiency of SPPs with the gain medium. Figure 6.4(c) shows that n_D is not necessarily required to be very large, while 1.49 is the best choice to achieve the most efficient plasmonic lasing; leaving from this value the lasing performance falls rapidly. The effect of grating duty cycle is also examined in Figure 6.4(d). It is shown that at $b/\Lambda \sim 0.8$ the surface emission reaches the maximal value.

Figure 6.5 lasing spectra of the device with optimized design of d_M , d_G , d_S , n_D , and b/Λ . Inset (a) plots the intensity distribution at peak wavelength and (b) plots the normalized peak field intensity versus the gain coefficient.

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Figure 6.5 displays the lasing spectra of the SE-DFB PL measured at two locations [‘O₁’ and ‘O₂’ shown in the insert (a) of Figure 5]. The optimized design of d_M , d_G , d_S , n_D , and b/Λ deduced from the above paragraphs are taken into calculation. It is found that the optimization introduces almost a slight shift (~ 3 nm) in the lasing wavelength. However, the SPP as well as the surface-emitting intensity is enhanced over five times. In insert (b) of Figure 6.5, we plot the normalized peak field intensity in DCL versus the gain coefficient. It is noted that the threshold gain coefficient, g_{th} , is less than 700 cm^{-1} , which is a very low value for plasmonic devices where high absorption is often encountered. In addition, we also calculated the quality factor of the SE-DFB PL. It is found that a quality factor up to 700 is achievable.

6.5 Conclusions and Discussion

In conclusion, an optimized design of a SE-DFB PL was presented. A dye polymer medium was used to provide amplification of localized SPPs confined by a thin metal layer, which surface was patterned as grating to obtain coherent optical feedback for the SPPs. In order to excite the localized SPPs to the surface of the SE-DFB PL, a high-index dielectric layer was proposed to decouple the confined SPPs from the metal grating. The lasing performance of the SE-DFB PL was examined and optimized through FDTD simulation. It is shown that a strong surface emission with threshold less than 700 cm^{-1} and quality factor up to 700 can be obtained from the proposed plasmonic laser.

CHAPTER 7

Conclusions and Recommendations

7.1 Conclusion

This thesis presents some active devices based on plasmonics which could be instrumental in future photonic integrated circuits. The possibility of realizing a SPP based laser has been discussed and proved. A simple structure based on IMI plasmonic waveguide was considered to realize plasmonic lasing. FDTD technique was first employed to study the propagation characteristics of IMI waveguide. An asymmetric excitation of SPP was considered in the IMI waveguide. As a result of this, an exchange of power of SP waves between the two interfaces of Ag-SiO₂ was observed; similar to what is observed in guided mode in conventional dielectric coupler. It was also observed that the coupling characteristics of SP waves are dependent of the thickness of metal layer and also the refractive index of dielectric layers. IMI waveguide of metal layer thickness ~ 60 nm was found to have propagation loss of less than 500 cm^{-1} . By introduction of a gain in one of the dielectric layer of the propagation loss can be compensated as a result of amplification of SP waves. Calculations suggest that the thickness of gain layer should be larger than 400 nm so that the SP waves are well confined. R6G doped PMMA was used as gain medium, it

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provides emission at about 590 nm under 532 nm excitation. The top layer too is chosen to be PMMA for index matching condition, it allows effective coupling of SP waves. Further, a coupled-mode model was developed to study the lasing characteristics of IMI waveguide. The theory has been valid because the coupling characteristics of SP waves inside the IMI waveguide are similar to that of a conventional dielectric coupler. A periodic grating is along the cladding layer is suggested to provide the feedback necessary for the lasing to take place. It is found that single-mode lasing can be supported in 300 μm long IMI waveguides with cleaved facets provided that the corresponding value of κ is around 80 cm^{-1} in order to suppress the influence of facet reflection. Further, an alternative design is discussed where the grating is replaced by a random feedback mechanism. The random feedback is designed such that it can sustain random lasing.

Another important plasmonic device discussed in the thesis is a modulator based on plasmonic Bragg reflector. A simple MIM waveguide is transformed into a Bragg reflector by replacing the insulator layer with periodic variation of two dielectrics. Because of two different dielectrics, the propagation constant of SPPs travelling through the waveguide varies periodically which leads to Bragg reflections. For this Bragg reflector to act as a modulator, we need to control the Bragg reflection externally. For this purpose, one of the alternating dielectrics inside the insulator layer was chosen to be electro-optic material, KNbO_3 in present case. KNbO_3 is a promising electro-optic material due to its large electro-optic coefficient and high breakdown voltage. Furthermore, ZnS is selected as its refractive index can be close to that of KNbO_3 at off-state so that the confined SPP waves can propagate freely along the insulator layer. The on-state is defined when the SPPs experience Bragg reflection and

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off-state is when SPPs travel freely similar to that in MIM waveguides. Transfer matrix method is employed to study the transmission characteristics of the Bragg reflector. Few important things to consider are that the difference between the reflectivity if on and off state should be maximum, the propagation loss should be minimum in both the states. Since the effective propagation depends upon the thickness of the insulator layer, individual thicknesses were varied to find the optimal performance of the device. Optimal thickness of KNbO_3 and ZnS was calculated to be 640 nm and 555 nm respectively and respective width of the layers was calculated to be 162 nm and 160 nm. With this optimized design, a reflectivity contrast larger than 65% was found between on and off state of the Bragg reflector. To achieve this reflectivity contrast 120 periods were required which makes the waveguide about 38 μm long. FDTD calculations were then performed to confirm the results obtained from the TMM results. It was observed that most of the light does not reach the end of the waveguide for the wavelength range of high reflectivity. Modulation response of the device was then calculated by applying an external sinusoidal bias of peak-to-peak voltage of 130 V. Modulation responses was then studied by assuming the biased device as standard RC circuit. It is seen that the peak reflectivity drops to 69% at -3dB point compared to 74% for steady state case.

Next, the plasmonic random laser discussed previously in the thesis was fabricated and tested. An IMI waveguide was fabricated with bottom dielectric as gain medium and top dielectric with random scatters. It was proved that, it is indeed possible to achieve SP lasing in a simple multilayer structure like one presented here. The exchange of energy of SP waves between the two dielectric-metal interfaces plays a very important role in the present device by coupling the spontaneous emission of

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bottom gain medium to the top layer where the SP waves undergo random feedback. Under the optical pumping of 532 nm, several peaks with linewidth less than 1 nm appeared around 590 nm at high pump intensity. Number of lasing peaks was seen to increase with pumping; this confirms that the observed lasing is random in nature. Far field profile shows collimated beam from the edge of the IMI waveguide. One should note that the metal layer do not contribute in the formation of any cavity which can support lasing because in present case the lasing is observed from the edge of the waveguide whereas if there is any formation of cavity because of metal it will be in the direction perpendicular to the emission direction. Moreover measurement in other direction other than the edge did not show any sign of lasing taking place confirming that the observed lasing is due to random cavity formation in the direction parallel to the metal film. Furthermore dependence of lasing threshold on excitation area was also studied to confirm random lasing. Presented experimental results confirm the possibility of achieving lasing emission based on SPPs. Plasmonic lasers form a very important component of future integrated circuits and this demonstration could be of great importance in realizing future devices.

Finally, we discuss yet another design for plasmonic laser. A surface emitting distributed feedback plasmonic laser is proposed. The main advantage of this design is that the emission is in one single direction unlike the previous IMI based structure where lasing emission could take place from both the edges. The structure consists of gain layer with a metal grating on the top. The emitted light from the gain medium is converted into SPPs and remain localized on to the metal air interface of the grating. A high-index decoupling layer is used to extract the localized SPPs. For an optimized design of the device, lasing peaks around 605 nm occur with linewidth less than 1 nm

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with a threshold less than 700 cm^{-1} . Since the SPPs are confined to the metal layer, the adjacent gain layer provides the necessary amplification to lower the threshold. The spacer layer plays an important role in present case because if the spacer layer is replaced with decoupling layer, SPPs will become unreachable. Moreover the emission is along the vertical direction making it a perfect surface emitting plasmonic laser.

The devices discussed in this thesis pave a route towards realization of integrated circuits based on surface plasmons. Some very fundamental and important components of integrated circuits have been proposed and their feasibility of actual realization has been proved.

7.2 Recommendations

Extensive researches have been reported in the field of plasmonics in past decade making it a hot field of research. Plasmonics based lasers and modulators make very important part of this field. In the area of plasmonic lasers, efforts are required to achieve better performance and stability. Out of various designs of lasing devices based on plasmonics, multilayer structures are simplest and easily integrable. But they require further consideration to enhance their performance. Modification in geometry or choice of materials can be two important factors. The random plasmonic laser fabricated was seen to have many lasing peaks around the central wavelength; this can be reduced by considering a ridge kind of waveguide or any other geometrical considerations. Moreover, using a grating in the cladding layer as discussed in the simulations can also reduce the number of lasing modes compared to random lasing. Fabrication of grating on a polymer layer remains an issue as the dimensions of

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grating can be small. An improved design of this device was presented later in the thesis in form of surface emitting plasmonic laser. The advantage of this design is its unidirectional emission. Also the metal grating provides a better confinement and feedback for SPPs. Experimental realization of this device needs to be done to verify the results presented in theoretical simulations and feasibility of proposed structure to work as a plasmonic laser.

Another device discussed here was plasmonic modulator based on Bragg reflector. Simulation results prove the usability of voltage controlled Bragg reflector to be used as plasmonic modulator. It is recommended to fabricate the device and test its response to verify the results claimed in theoretical simulations. Fabrication route of the device has already been discussed in the relevant chapter. Most important issue in present case is the response of KNbO_3 to the external bias. One has to take in account the voltage response of the insulator layer to avoid material breakdown.

From these recommendations, experimental verification of the devices presented here needs to be done. Another important point is that the plasmonic laser presented here optically pumped. To have a lasing source which can be integrated to circuits along with other components, one needs to have an electrically pumped plasmonic laser. There have not been many reports of electrically pumped plasmonic laser, so it forms a very important area of research. Realization of an electrically pumped plasmonic laser is very important to achieve SPPs based integrated circuits.

Author's publications:

1. **Ashwani Kumar**, S. F. Yu, X. F. Li, and S. P. Lau, "Surface plasmonic lasing via the amplification of coupled surface plasmon waves inside dielectric-metal-dielectric waveguides," *Optics Express* **16** (20), 16113-16123 (2008).
2. **Ashwani Kumar**, S. F. Yu, and X. Li, "Design and analysis of a surface plasmon polariton modulator using the electro-optic effect," *Applied Optics* **48**, 6600-6605 (2009)
3. **Ashwani Kumar**, S. F. Yu, and X. Li, "Random laser action in dielectric-metal-dielectric surface plasmon waveguides," *Applied Physics Letters* **95**, 231114 (2009).
4. X. Li, S. F. Yu, and **Ashwani Kumar**, " A surface-emitting distributed-feedback plasmonic laser," *Applied Physics Letters* **95**, 141114 (2009)
5. X. Li, S. F. Yu, and **Ashwani Kumar**, " Excitation and Optimization Modeling of Surface Plasmon Polaritons in a Concentric Circular Metallic Grating Film," (accepted for publication in *Plasmonics*).
6. Rakesh G. Mote, S.F. Yu, **Ashwani Kumar**, W. Zhou, and X.F. Li, " Experimental Demonstration of Near-Field Focusing of a Phase Fresnel Zone Plate (FZP) Under Linearly Polarized Illumination," (communicated to IEEE, *Photonics Technology Letters*).

Appendix A: The Reverse Pole Method.

Appendix A

The Reflection Pole Method:

Plasmonic structure with semi infinite multilayer can be studied by Reflection Pole Method (RPM)⁸⁸. The RPM detects both leaky and guided mode by monitoring the phase of the reflection coefficient denominator or equivalently the reflection-coefficient poles as a function of normalised longitudinal wave vector component or effective refractive index. The RPM uses transfer matrix formulation to obtain the reflection coefficient.

Transfer matrix formulation:

Fig. A1 Multilayer Plasmonic structure

Since the plasmon waves are TM mode, we write the magnetic fields in different regions.

$$H_{yi} = \{A_i \exp[-k_{xi}(x - x_{i-1})] + B_i \exp[k_{xi}(x - x_{i-1})]\} \exp[-j\beta z] \quad i = 0, 1, 2, 3, \dots \quad (A1)$$

Where $k_{xi} = \sqrt{\beta^2 - \epsilon_i k_0^2}$

Appendix A: The Reverse Pole Method.

At each boundary the magnetic field, H_{yi} and the electric field $E_{zi} = \frac{1}{j\omega\epsilon_i} \frac{\partial H_{yi}}{\partial x}$

should be continuous.

Applying these boundary conditions we have,

$$\begin{bmatrix} A_n \\ B_n \end{bmatrix} = \sum_0^{n-1} T_i \begin{bmatrix} A_0 \\ B_0 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} A_n \\ B_n \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} A_0 \\ B_0 \end{bmatrix} \quad (\text{A2})$$

$$\text{Where } T_i = \frac{1}{2} \begin{bmatrix} \left(1 + \frac{\epsilon_{i+1}}{\epsilon_i} \frac{k_{xi}}{k_{x(i+1)}}\right) \exp(-k_{xi}d) & \left(1 - \frac{\epsilon_{i+1}}{\epsilon_i} \frac{k_{xi}}{k_{x(i+1)}}\right) \exp(k_{xi}d) \\ \left(1 - \frac{\epsilon_{i+1}}{\epsilon_i} \frac{k_{xi}}{k_{x(i+1)}}\right) \exp(-k_{xi}d) & \left(1 + \frac{\epsilon_{i+1}}{\epsilon_i} \frac{k_{xi}}{k_{x(i+1)}}\right) \exp(k_{xi}d) \end{bmatrix}$$

The complex reflection coefficient R and transmission T is given by

$$\begin{bmatrix} R_n \\ 1 \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} 0 \\ T_0 \end{bmatrix} \quad (\text{A3a})$$

$$\begin{bmatrix} T_n \\ 0 \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} 1 \\ R_0 \end{bmatrix} \quad (\text{A3b})$$

$$\text{So } R_0 = \frac{A_0}{B_0} = -\frac{t_{21}}{t_{22}} \quad (\text{A4})$$

The reflection coefficient R_0 is a function of complex propagation constant

$$\beta = (n_r + in_i)k_0$$

Appendix A: The Reverse Pole Method.

The guided plasmon modes are the modes which propagate in z direction and exponentially decay in x direction away from metal. The guided modes correspond to the resonance of the layered waveguide structure, which happens at the poles of the reflection coefficient R . the poles of the reflection coefficient are the solutions of $t_{22}(\beta) = 0$.

Finding the solution of $t_{22}(\beta) = 0$ is numerically challenging. The RPM method monitors the phase of $t_{22}(\beta)$ as a function of real part of the effective index. The plasmon modes correspond to rapid change of the phase of $t_{22}(\beta)$.

Using RPM one can find a guess for real part of effective refractive index and then use that guess to solve the equation $t_{22}(\beta)$ exactly.

Example: We use the RPM just discussed above to solve the plasmonic structure as shown below for $\lambda=632.8$ nm.

Fig.A2 Plasmonic structure with metal sandwich between two different dielectrics

We have from the transfer matrix formulation

$$\begin{bmatrix} A_2 \\ B_2 \end{bmatrix} = T_1 T_0 \begin{bmatrix} A_0 \\ B_0 \end{bmatrix} \quad (A5)$$

Appendix A: The Reverse Pole Method.

For $d=200\text{nm}$, the plot of phase of $t_{22}(\beta)$ as a function of real part of the effective index is shown below.

Fig. A3 Phase plot of $t_{22}(\beta)$ as a function of real effective index

We clearly see that there is a rapid change in phase near $n=1.55$ and $n=2.14$. Taking these two as initial guess and solving $t_{22}(\beta)=0$, we get following result.

Table 1 Comparison of results obtained with ref⁸⁹

	Reference 78	Program developed
n_1	$1.5507 + 0.0001615 i$	$1.55070705885963 + 0.00016394803107 i$
n_2	$2.14 + 0.0325 i$	$2.18416548582882 + 0.03542298546572 i$

Appendix B: Four Level System to Two Level System.

Appendix B

Four Level System to Two Level System

Figure B1 The energy level diagram for R6G laser⁹⁰.

Figure B1 shows the simplified energy-level diagram of R6G dye system. The states shown on the left are of a four-level system along with the triplet states in the right. The ground level is split into two vibronic levels with population distribution governed by Boltzmann distribution. The two factors α and β added up to unity. The transition response of the gain system described by the energy-level model shown above can be written as:

$$\frac{dN_3(z,t)}{dt} = R_{13}(z,t)\alpha N_1(z,t) - (\tau_{R3}^{-1} + K_{32})N_3(z,t) \quad (B1a)$$

$$\frac{dN_2(z,t)}{dt} = K_{32}N_3(z,t) + \omega_a\beta N_1(z,t) - (\omega_e + \tau_{R2}^{-1})N_2(z,t) \quad (B1b)$$

$$N_1(z,t) = N_{dye}(z,t) - N_2(z,t) - N_3(z,t) \quad (B1c)$$

Appendix B: Four Level System to Two Level System.

where the transition rate R_{13} , W_a and W_e can be expressed as

$$R_{13}(z, t, \lambda_p) = A_{eff}^{-1} \frac{\sigma_p^{13}(\lambda_p)}{h \nu_p} P_{pump}, \quad (B2a)$$

$$W_a(z, t, \lambda_s) = A_{eff}^{-1} \frac{\sigma_s^a(\lambda_s)}{h \nu_s} P_s^0(\lambda_s) S_A(z, t), \quad (B2b)$$

$$W_e(z, t, \lambda_s) = A_{eff}^{-1} \frac{\sigma_s^e(\lambda_s)}{h \nu_s} P_s^0(\lambda_s) S_A(z, t). \quad (B2c)$$

N_i ($i=1,2,..$) represent the population densities at the i^{th} energy level. τ_{Ri} (for $i = 1, 2, \dots$) is the carrier recombination lifetime of the population density N_i at i^{th} energy level and K_{32} is the non-radiative transition of population densities between 3rd and 2nd levels. K_{ISC} describes the process of “intersystem crossing” in which the carriers can cross over to triplet states and is neglected for simplification.

The above four-level model can be reduced to an equivalent two-level model provided that the lifetime of N_3 is much shorter than that of the other energy levels⁶⁷. Using this assumption, it is possible to write

$$dN_3(z, t)/dt = 0. \quad (B3)$$

Substituting (B3) into (B1a), it can be shown that (B1b) can be simplified to

$$\frac{dN_2(z, t)}{dt} = \left[\frac{K_{32} R_{13}(z, t) \alpha}{\tau_{R3}^{-1} + K_{32}} + \omega_a \beta \right] N_1(z, t) - [\omega_e + \tau_{R2}^{-1}] N_2(z, t) \quad (B5)$$

Appendix B: Four Level System to Two Level System.

If the energy between the two vibronic levels is very small, we just have a single level N_1 , and the system has high quantum efficiency (i.e., $K_{32} \gg \tau_{R3}^{-1}, R_{13}$), (B5) can be further simplified to the following equation:

$$\frac{dN_2(z,t)}{dt} = [R_{13}(z,t) + \omega_a]N_1(z,t) - [\omega_e + \tau_{R2}^{-1}]N_2(z,t) \quad (B6)$$

Using the same assumptions in the derivation of (B6), (B1c) can be simplified to:

$$N_1(z,t) + N_2(z,t) \cong N_{dye}(z,t) \quad (B7)$$

Hence, the original four-level system of R6G dye gain medium can be approximated by (B6) and (B7) – the simplified two-level system given.

Appendix C

Photoluminescence Setup

The schematic diagram of the photoluminescence setup is shown in figure C1. It consisted of Nd:YAG pulse laser source (frequency tripled 355 nm, 10 Hz), harmonic generator, attenuator, mirrors, lenses and monochromator-photodetector set up. The output of the Nd:YAG laser was pumped into the sample at 90° , focused by a cylindrical lens of focal length 10 cm. The emission at the facet of the sample was collimated into a slit input assembly of a monochromator, through a 5 cm plano-convex lens. Beam exited at the slit was detected by a built-in trans-impedance amplifier silicon detector, mounted at the slit exit. Signal output from the

Figure C1 Schematic diagram of the Photoluminescence measurement setup

Appendix C : Photoluminescence Setup.

photodetector can be detected using either a Merlin 70100 or a SR510 analog lock-in amplifier. Reference signal from the laser pulse synchronize the photodetector and lock-in amplifier reading. The spectrum of the sample output was obtained by the diffraction grating in the monochromator. The data was fed into the computer, recorded and analyzed using a computer program written in Labview.

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