Surface Plasmon Polariton Based Polarization Modulators
Using Metal-Polymer Waveguides

by

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Graduate Department of Electrical And Computer Engineering
University of Toronto

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Abstract

A tunable polarization modulator based on the periodic metal strips embedded in a polymer waveguide is presented. The periodic metallic structure is analyzed by Finite Element simulation (COMSOL). The calculation results show that the giant birefringence is formed by the selective cut-off of TE polarization over TM polarization, which makes it possible to design an efficient polarization modulator with a short conversion length. The metallic strips are made by using four-layer lift-off fabrication technology. The transmission and group indices of TE and TM modes are measured. However, it is observed that TE and TM modes cut off at same time, which does not agree with our predictions. The reason for failure is that the change in refractive indices is different from what we expected, which makes the device perform in opposite way. Finally, further suggestions are provided to modify the design so that the device can achieve its expected function.
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<tr>
<td>$\tilde{n}$</td>
<td>Normal to the surface</td>
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<tr>
<td>$E$</td>
<td>Electric fields</td>
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<tr>
<td>$\sigma$</td>
<td>Surface-charge density</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>Permittivity of free space</td>
</tr>
<tr>
<td>$k_{sp}$</td>
<td>Wave vector of SPP mode</td>
</tr>
<tr>
<td>$k_0$</td>
<td>Wave vector of free-space photon</td>
</tr>
<tr>
<td>$\varepsilon_m$</td>
<td>Permittivity of the metal</td>
</tr>
<tr>
<td>$\varepsilon_d$</td>
<td>Permittivity of the dielectric material</td>
</tr>
<tr>
<td>$\varphi_x$</td>
<td>Phase term corresponding to $x$ polarized component</td>
</tr>
<tr>
<td>$\varphi_y$</td>
<td>Phase term corresponding to $y$ polarized component</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular frequency</td>
</tr>
<tr>
<td>$A_x$</td>
<td>Independent amplitude of $x$ component</td>
</tr>
<tr>
<td>$A_y$</td>
<td>Independent amplitude of $y$ component</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Cavity internal loss</td>
</tr>
<tr>
<td>$n$</td>
<td>Refractive index</td>
</tr>
<tr>
<td>$R$</td>
<td>Mirror reflectivity</td>
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<tr>
<td>$\beta_{TM}$</td>
<td>Propagation constants of TM mode</td>
</tr>
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</table>
\(\beta_{TE}\) Propagation constants of TE mode

\(n_{TM}\) Effective indices of TM mode

\(n_{TE}\) Effective indices of TE mode

\(P\) Period of the grating

\(h\) Height of each silver strip

\(w\) Width of each silver strip

\(w_g\) Width of the polymer waveguide

\(\Delta n\) Change in the refractive index of the cladding polymer

\(I\) Current

\(R\) Resistance of the heater (in Eq. [4.1] and Eq. [4.3])

\(C_p\) Heat capacity of copper

\(A\) Cross section area

\(L\) Length of the wire

\(D\) Density of copper

\(\Delta\) Laplacian operator
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<th>Definition</th>
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<tr>
<td>1D</td>
<td>One Dimensional</td>
</tr>
<tr>
<td>ATR</td>
<td>Attenuated Total Reflection</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal-Oxide-Semiconductor</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>LOR</td>
<td>Lift-off Resist</td>
</tr>
<tr>
<td>rpm</td>
<td>rotations per minute</td>
</tr>
<tr>
<td>LRSPP</td>
<td>Long-Range Surface Plasmon Polariton</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>SPPs</td>
<td>Surface Plasmon Polaritons</td>
</tr>
<tr>
<td>SPR</td>
<td>Surface Plasmon Resonance</td>
</tr>
<tr>
<td>TE</td>
<td>Transverse Electric</td>
</tr>
<tr>
<td>TM</td>
<td>Transverse Magnetic</td>
</tr>
<tr>
<td>TMAH</td>
<td>Tetramethylammonium Hydroxide</td>
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Chapter 1

Introduction and Motivation

1.1 Background

In recent years, there is a significant effort in developing nano-scale optical devices for photonic integrated circuits, which is driven by the desire for high-integration density on a chip. One of the popular implementations of nano-scale optical circuit elements is silicon based device with an ultra-high refractive index contrast. However, the optical field confinement in these kinds of devices is limited by diffraction to about half the effective light wavelength. In contrast, metal with negative dielectric permittivity (at optical frequency) is considered as a solution for overcoming the optical diffraction limit. The localized plasmons excited on the metal surface have a feature of confining electromagnetic waves over dimensions much smaller than the wavelength. Moreover, plasmonic circuits also offer the ability of sending both electric and photonic signals along the same circuitry. As a result, plasmonics is an area for developing the prospective type of optical integrated device combining the ultra fast operating speed and the sub-wavelength physical scale comparable to electronics.

Surface Plasmon Polaritons (SPPs) are electromagnetic waves coupled to electron oscillations that propagate along a metal-dielectric interface. The polariton is highly confined at the interface and decays exponentially in the direction perpendicular to the surface. According to
the boundary condition
\[ \vec{n} \cdot (\vec{E}_2 - \vec{E}_1) = \sigma / \varepsilon_0, \]  

where \( \vec{n} \) is the normal to the surface, \( E_1 \) and \( E_2 \) are electric fields on either side of the surface, \( \sigma \) is a surface-charge density, and \( \varepsilon_0 \) is the permittivity of free space, the high density of the surface charge requires that the electric field be normal to the surface. Thus, SPPs only exist for transverse magnetic (TM) polarized light. By solving Maxwell’s equations under the appropriate boundary conditions at single interface, we can obtain the dispersion relation SPPs

\[ k_{sp} = k_0 \sqrt{\frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m}}, \]  

where \( k_{sp} \) is the wave vector of SPP mode, \( k_0 \) is the wave vector of free-space photon, \( \varepsilon_m \) and \( \varepsilon_d \) are permittivities of the metal and dielectric materials, respectively.

Figure 1.1 The dispersion relation of a SPP mode.

The confinement of the SPPs to the surface demands the real parts of the permittivities of the metal, \( \varepsilon_m \), and the dielectric material, \( \varepsilon_d \), have opposite signs [1]. The dispersion relation for a SPP mode is shown in Figure 1.1. The wave vector of SPP mode, \( k_{sp} \), is always greater than that of a free-space photon at the same frequency, \( k_0 \). ( \( k_0 = \omega / c \) ). This characteristic leads to shorter wavelength of SPP wave relative to the free-space wavelength. Thus, the special techniques, such as grating or prism coupling, are required to overcome the propagation constant mismatch to excite the SPP mode by using light.
1.2 SPP Waveguides

Although SPPs have been studied for several decades [2], considerable interest in this field emerged recently because SPPs can strongly confine the light at subwavelength scales as a consequence of the evanescent SP wave in the perpendicular direction, which prevents power from dispersing away from the surface. This can allow integrated photonic circuits made with SPP waveguides to be much smaller than dielectric photonic circuits. Various types of SPP waveguides have been proposed. These include metal films [3, 4], metal strips [5-7], and V grooves in metal substrates [8-10]. When a SPP mode propagates on the metal surface, it also suffers from attenuation owing to losses arising from absorption in the metal. SPP waveguides must balance losses with optical confinement. The theoretical studies demonstrate that metal strips surrounded by a dielectric cladding, as shown in Fig.1.2a, can support symmetric and asymmetric modes. The symmetric modes are subject to low propagation loss and can propagate over millimeter long distances for a thin metal stripe thickness on the order of 20 nm [5]. So it is
called long-range SPP (LRSPPP) mode. The low attenuation is due to the facts that the confinement to the lossy metal decreases with decreasing metal film thickness, and the mode spreads and evolves into the plane wave in the homogeneous dielectric media. In contrast, another type of plasmonic waveguide offering sub-wavelength confinement is triangular (V) groove on a metal substrate (Fig.1.2b). Since the narrower gaps between two metal surfaces support the SPP modes with higher effective indices and the light tends to be confined in high refractive index region, the SPP mode exists at the groove bottom. Experimentally, at near-infrared wavelengths, a bound mode with long propagation length (~100µm) and well localization (mode width ~ 1.1µm) have been demonstrated in a 0.6µm wide and 1µm deep V-groove in gold [10]. This showed the perfect trade-off between the low loss and the well confinement. Recently, a hybrid plasmonic waveguide formed by a dielectric cylinder above a metal surface (Fig.1.2c) were developed to achieve both nano-scale light confinement and long propagation distance [11]. However, the cylinder structure made it hard to fabricate such a device. In order to simplify the fabrication processes, a rectangular waveguide with a silicon-on-insulator (SOI) rib separated from a metal cap by a narrow SiO₂ gap (Fig. 1.2d) has been presented in ref [12]. For the case of a relatively thick SiO₂ layer (~ 50nm), when the core width increases, the more power of TM mode is confined in Si region. The strong mode confinement in dielectric layer leads to long propagation distance that is on order of 100 µm at wavelengths near 1550 nm. Furthermore, this structure also has the potential to realize a low-voltage optical modulator when the gap material has a high electro-optical coefficient.

1.3 SPP modulation Devices

Integral to a photonic integrated circuit is an optical modulator. In the early attempts, many of SPP modulators were based on surface plasmon resonance (SPR), in which the surface plasmonic wave was excited by attenuated total reflection (ATR) and the reflected light vanished. The excitation condition of SPR sensitivity depends on the refractive indices and thicknesses of the
metallic and dielectric materials near the metal-dielectric interface. In some works, electro-optical materials were used as active dielectric layers on metals [13-17]. Because of the large birefringence, liquid crystal is also regarded as one of the best materials for a SPP light modulator [18, 19]. Another mechanism of modulation is “gap control.” which can be achieved by piezo-electrically varying the prism-metal gap [20]. All these configurations require bulky experimental apparatus, prism, and are difficult for chip-scale integration. Instead of the electro-optic effect, Schottky barrier diodes have also been used in SPR modulators to induce change in refractive index by free carrier injection [21]. Since a grating was used to modulate the reflected light in this device, it also was incompatible with an integrated waveguide. Jannson et al. presented an idea of SPR modulation in an integrated optical waveguide, in which the SPR due to TM traveling light was shifted through a change in the refractive index of an electro-optic polymer [22].

Recently, thermo-optic modulation and switching using a Mach–Zehnder interferometer and a directional coupler, respectively, were realized by long-range SPP gold stripes waveguides embedded in polymer [23]. Compared with conventional waveguide, the metallic stripe waveguide can carry both SPP wave and electrical control signal. The devices were reported to have low driving powers, high extinction ratios, and moderate response times. A plasmonic planar modulator based on interference of SPPs waves propagating on the interface between silver and electro-optic barium titanate was also demonstrated in [24]. Developing silicon (Si)-based plasmonic device is desired because of its fabrication compatibility with complementary metal-oxide-semiconductor (CMOS) technologies and potential integration into existing Si-based electronic circuits. Electrical control of light transmission in a field effect Si modulator based on multimode interferometry in a four-layer Ag-oxide-Si-Ag waveguide has been shown in [25]. In the absence of an applied voltage at the gate, the waveguide supported two modes: a photonic mode and a plasmonic mode. When a bias was applied, the photonic mode was forced into cutoff. The observed amplitude modulation ration approached 10 dB in device volumes of half a cubic wavelength with femto-joule energy. In addition, quantum dots have been used in the plasmonic planar devices to perform efficient all-optical modulation of SPP transmission by influencing the
plasmon-induced absorption in the quantum dots [26].

### 1.4 Polarization Modulation Devices

In order to meet the demand for ultra-small photonic communication systems, high-index-contrast dielectric waveguides are frequently used to realize highly confined optical modes. However, the large difference in refractive index and the asymmetry between the waveguide structures along the x and y axes result in birefringence. As a consequence, the critical parameters of many integrated optical components are sensitive to the polarization state of light. Therefore, it is possible to control the optical transmission by varying the polarization state of the light. There are two types of the polarization rotators: passive and active rotators. In recent years, much effort has been devoted to design more compact passive polarization rotators [27-33]. Although the passive polarization rotator is simple and its length could be short (<10 µm) [31, 33], an active polarization rotator would allow for dynamical polarization rotation using electro-optic or thermal-optic effects. A device that provides modulation of the state of polarization can be expected to serve a variety of useful functions, such as polarization stabilization and interferometry. Previous examples of active dynamic polarization rotators have been made in anisotropic crystals such as lithium niobate and AlGaAs-GaAs [34, 35]. However, owing to the low birefringence of these kinds of crystals, the lengths of recent active rotators are very long, often on the order of several millimeters.

### 1.5 Motivation

To make a short polarization rotator, a large birefringence is required. Aside from birefringence arising from material properties, birefringence can also result from specifically designed waveguides and the periodic multilayer isotropic materials. The latter is referred to as
“form-birefringence”. The giant birefringence in multi-slot Si waveguides and metallic nanoslit arrays has been recently reported [37, 38]. The birefringence for metal-dielectric structures can be large because the two orthogonal polarizations have different characteristics. The TM polarization can excite SPPs, while the transverse electric (TE) polarization cannot. In addition, the cut-off properties of the TE and TM modes would be different. Although SPP passive polarization rotators have been demonstrated [33], a tunable or active SPP polarization rotator has not been reported.

In this work we design, fabricate, and measure a tunable polarization rotator by using the periodic metal strips embedded in a polymer waveguide. The design uses the giant birefringence formed by the periodic metal structure, which can cause a high polarization conversion efficiency, resulting in a short conversion length.

1.6 Thesis Outline

This thesis is organized as follows. Chapter 2 deals with the theoretical and simulations of the device. The one dimensional (1D) version of the device is first analyzed to explain the principle of operation of the device. Then the waveguide structure is simulated numerically. In Chapter 3, we explain the fabrication process that was developed to make the proposed design. Chapter 4 shows our experimental set up and transmission measurement results. In Chapter 5, conclusions, lessons, and the suggestions for the future work are provided.
Chapter 2

Theory and Simulation

2.1 Polarization Rotators

In electromagnetics, polarization is a physical property describing the orientation of the oscillation of the electric field (E-field) vector. When light travels in an isotropic medium, in most cases, the orientation of the E-field is perpendicular to the direction of propagation. That is called a transverse wave. The polarization of a transverse wave may be fixed in a single direction or may change with time. In the former case, the wave is said to be linearly polarized. The latter case is called elliptically or circularly polarized. Any transverse wave can be split into two waves with orthogonal linear polarization. The amplitudes and phase differences of two waves determine the state of polarization. If we assume the wave propagates along $z$ axis, for a transverse wave, the E-field vector must be in $x$-$y$ plane. The two perpendicular components of electric vector are given by:

$$E_x = A_x \cos(\omega t + \varphi_x)$$  \[2.1\]

$$E_y = A_y \cos(\omega t + \varphi_y)$$  \[2.2\]

where $A_x$ and $A_y$ represent two independent amplitudes. $\varphi_x$ and $\varphi_y$ are phase term corresponding to $x$ and $y$ polarized components, $\omega$ is angular frequency, and $t$ is time. When
two components are in phase \((\varphi = \varphi_y - \varphi_x = 0)\) or in anti-phase \((\varphi = \varphi_y - \varphi_x = \pm \pi)\), the superposition of components forms a linearly polarized wave. If \(\varphi = \varphi_y - \varphi_x = \pm \pi / 2\) and \(A_x = A_y\), the E-field vector rotates with a fixed radius. This is circular polarization. In general, the two components may not have equal amplitudes, so the E-field vector traces an ellipse, and the polarization state is called elliptical polarization.

From the above analysis, it is clear that change in amplitude and phase of the orthogonal polarization components always causes the change of state of polarization. Normally, when light propagates in an anisotropic medium or in a waveguide, since the phase velocities for two polarization components are different, there is a phase mismatch between two components. This means the output polarization is not necessarily identical to the input. Assuming a waveguide that supports a TE and TM modes, when the two modes have traversed through a length of \(L\), the phase mismatch is

\[
\varphi = (\beta_{TM} - \beta_{TE}) \cdot L
\]

where \(\beta_{TM}\) and \(\beta_{TE}\) are the propagation constants of TM and TE modes, respectively. At certain values of \(L\), the phase mismatch can equal to 0 or \(\pi\), and the output would be linearly polarized. Alternatively, we can fix the \(L\), excite both polarizations at the input and change the phase mismatch \(\varphi\) by changing the refractive index of waveguide material. Then the polarization state of output light can be modulated. If TE and TM modes have similar amplitudes and the change in phase mismatch is \(\pi\), then the polarization direction of the output will be rotated by 90°. The rotation of polarization can be used to design a polarization modulator.
2.2 Analytical analysis of 1D metal grating.

Figure 2.1. Illustration of the geometry of the 1-D infinite grating. $P$ is the period and $q$ is the fill factor. Light propagates into/out of the page.

Our design of the polarization rotator uses metallic strips embedded in a waveguide to generate the birefringence. In this section, we describe the general characteristics of this type of structure in 1D by way of an analysis of metal-dielectric gratings. The analysis follows that in [36]. Figure 2.1 shows a schematic of the 1D infinite grating that is a periodic stratified consisting of layers of a material with refractive index $n_1$ sandwiched between layers of dielectrics with refractive index $n_2$. In this figure, $P$ represents period and $q$ represents the ratio of the thickness of the $n_1$ layer to the period. If we assume that the propagation of incident light is parallel to the layers of the medium, the effective refractive indices of two polarized mode are given by

$$n_{TE} = [n_1^2 q + n_2^2 (1 - q)]^{1/2}$$

and

$$n_{TM} = [(1/n_1^2)q + (1/n_2^2)(1 - q)]^{-1/2}$$

where $n_{TM}$ and $n_{TE}$ are the effective indices of TM and TE modes, respectively for $P << \lambda$. [36].
The design concept of a polarization rotator is based on the phase mismatch between the TE and TM polarized modes as discussed in section 2.1. In order to obtain high efficiency of the polarization modulation, it is necessary to increase the change in magnitude of phase mismatch when changing the refractive index of the material of the waveguide. To give the detailed analysis, we define the feature parameter $\Gamma$

$$\Gamma = d(n_{TM} - n_{TE})/dn_2,$$  \hspace{2cm} [2.6]

where $dn_2$ represents the infinitesimal change in the refractive index of the dielectric. $\Gamma$ describes the magnitude of change in the phase mismatch corresponding to the change in the refractive index of the dielectric. For the polarization modulator, the conversion length to accomplish $90^\circ$ rotation modulation is described by $k_0 \Delta(n_{TM} - n_{TE}) L = \pi$, therefore $L = \lambda/[2\Delta(n_{TM} - n_{TE})]$. Compared with the definition of $\Gamma$ in Eq. 2.6, we see that the conversion length is related to the parameter $\Gamma$,

$$L = \lambda/(2\Delta n \Gamma).$$  \hspace{2cm} [2.7]

where $\Delta n$ is the change in the refractive index of the dielectric. Equation [2.7] indicates that the larger $\Gamma$ is, the shorter the conversion length. Hence, we expect a high $\Gamma$. Figure 2.2 (a) shows the plot of calculated $\Gamma$ as a function of the ratio of the opening to period $q$ for a dielectric grating. For the calculation, $n_2 = 1.48$ and $n_1 = 3.4$. The calculation indicates that, in general, $\Gamma < 1$ for a dielectric grating regardless of the value of $q$. It is also shown that the curve is broad and smooth.

On the contrary, if the $n_1$ layers are replaced with a metal, $\Gamma$ can be exceed unity. This is because metals, such as gold and silver, have large negative permittivity in the infrared and visible wavelength range. Figure 2.2 (b) shows $\Gamma$ as a function of $q$ for a grating consisting of a metal with refractive index of 0.12-10.52 (representing silver at 1550 nm) and a dielectric of refractive index $n_2 = 1.48$. In the figure, $\Gamma$ reaches a maximum of 4.3, which more than 4 times larger than what is possible in a dielectric grating. Compared to Figure 2.2 (a), $\Gamma$ for the metal-dielectric also depends more strongly on $q$. This property also implies that the polarization modulation can be made by relatively small changes in the refractive index. The effective indices of the TM and TE modes as functions of $q$ for the metal-dielectric grating are
plotted in Figure 2.3. It is shown that the TE mode cuts off while the TM mode does not. Compared to Figure 2.2 (b), the maximum of $\Gamma$ and the cut-off of the TE mode take place at the same $q$. That indicates the large $\Gamma$ may result from the cut-off of the TE mode. These results indicate that it is possible to design a polarization device based on metal-dielectric gratings, which can be several times shorter than a device based on dielectric gratings.

Figure 2.2. (a) Calculation of $\Gamma$ vs. $q$ for a dielectric grating. The refractive indices are indicated in the figure. (b), Calculation of $\Gamma$ vs $q$ for a metal-dielectric grating.

Figure 2.3, Plots of effective indices for (a) TM and (b) TE as functions of $q$ for a metal-dielectric grating.
2.3 Proposed device and 3D simulations

Inspired by the properties of the metal-dielectric gratings, we propose a polarization modulator shown in Figure 2.4. Silver strips are embedded in a regular polymer waveguide that works as the input and output sections. The structure is buried in a low refractive index cladding material. Polymer was chosen as waveguide material because it can be fabricated relatively easily. We chose to use silver, since it has lower loss than another common metal, gold, at a wavelength of 1550 nm [39]. In this structure, propagation of light through the waveguide experiences a form-birefringence. In Figure 2.4, $L$ denotes the length of the grating section; $P$ denotes the period of the grating, $h$ and $w$ denote the height and width of each silver strip, respectively. $w_g$ denotes the width of the polymer waveguide.

The waveguide can become cut-off for the two polarizations. The selective cut-off of one polarization over another is essential to obtaining a large value of $\Gamma$. The grating period beyond which the waveguide is cut off depends on the aspect ratio of the metal strip. To build small waveguide, short period is expected. On the other hand, a high aspect ratio makes the device more difficult to fabricate. By considering the trade-offs between these two issues, we chose $w=80$ nm and $h=500$ nm (aspect ratio 6.25:1) in all of the analyses of this paper. The wavelength is 1550 nm, and refractive indices for the polymer waveguide and cladding material are 1.54 and 1.47, respectively.

![Figure 2.4. Schematic of the proposed polarization modulator.](image)

The parameters that we need to design are the period and length of the metal-dielectric
grating in the polymer waveguide. First, we calculated the effective indices of the two orthogonally polarized modes for the different periods of the metallic array using a finite element method (FEM) mode solver (COMSOL). Figure 2.5 shows the modal E-field intensity distributions of the lowest order TE and TM polarized modes for the device with a period of 707nm. It is clear that the TM mode (which excites the SPPs) is peaked at the metal-dielectric interfaces and propagates along the interfaces. Its mode index is usually greater than the refractive index of the dielectric. On the contrary, the TE mode is close to zero at the metal surface and most of the field is confined in the dielectric regions. The TE mode is a typical dielectric mode with an effective index that is less than the refractive index of the dielectric. The large propagation constant difference between the TE and TM modes results in a giant birefringence that is larger than 1.

Figure 2.5. (a) TE mode profile in the array section. (b) Cross section of the TE mode profile. (c) TM mode profile in the array section. (d) Cross section of the TM mode profile.
The $\Gamma$ parameter as function of period estimated by the formula, $\Gamma = \Delta (n_{TM} - n_{TE})/\Delta n$, is shown in the Figure 2.6. In the calculation, $\Delta n$, which is the change in the refractive index of the cladding polymer, is chosen to be 0.01 and the refractive index of the core polymer is assumed to be fixed. It is observed that $\Gamma$ reaches a maximum of 10.35 around the period of 707 nm. The conversion length corresponding to the maximum $\Gamma$ parameter is calculated to be 7.5 $\mu$m when $\Delta n$ is 0.01. The large value of $\Gamma$ is due to the cut-off of the TE mode (Figure 2.6), which causes the large change in ($n_{TM} - n_{TE}$) near the period of 707nm. The result shows that a tunable polarization rotator based on metallic gratings with a period of 707 nm can be shorter than 10 $\mu$m. It is also found from Figure 2.7 that the loss of TE mode is around 0.68 dB/$\mu$m. Since the change in the refractive index of the cladding material is limited, the period (707 nm) with relative high loss is selected to ensure the TE mode cut off efficiently. On the contrary, the TM mode has much lower loss of 0.012dB/$\mu$m at the period of 707nm.

![Figure 2.6. Plot of $\Gamma$ parameter as a function to the period of the metallic array.](image)
Figure 2.7. Plot of the real and imaginary parts of the TE mode as a function the period of the metallic array.
Chapter 3

Fabrication

3.1 Process Flow

To fabricate our device, we used steps of aligned electron-beam (e-beam) lithography and lift-off. Even though wet chemical etching can be used to create metal patterns, the process is not reliable for building high-aspect ratio features. In a lift-off process, patterns are created by washing way the sacrificial layer, usually a resist, on which the metal is deposited, and leaving only the film that was contacted directly with the substrate. A single layer technique is the simplest lift-off procedure, where only one layer of resist is used. However, in the case where the resist layer must be thin, metal can be deposited on the sidewall of the opening of the resist, which makes lift-off difficult to complete. To avoid that disadvantage, a lift-off resist (LOR) assisted lift-off technique is developed. LOR is not photo- or e-beam sensitive but is freely soluble in aqueous tetramethylammonium hydroxide (TMAH) solvent. In this bi-layer process, a film of LOR is coated first and then a layer of resist is deposited over this layer and patterned through photo- or e-beam exposure. The LOR layer dissolves isotropically in the developer to undercut the edge of the resist profile. This prevents the sidewall from being covered with metal during the metallization.
In this work, we need to build a metal structure buried in the polymer waveguide, so we used a four-layer lift-off process. An e-beam sensitive material was used as the waveguide core-layer material. We used ZEP, which has a refractive index of 1.535 around 1.55 μm as the waveguide core. The cladding layer was chosen to be UV-curable resin adhesive OG-603 from Epoxy Technology. At a 1550 nm wavelength, the refractive indices of OG-603 was around 1.48. The fabrication process flow is described in Figure 3.1.

First, OG-603 was deposited as the lower cladding material. Then three layers of ZEP/LOR/ZEP were spin-coated on the adhesive layer. The polymer waveguide structure was formed in the lower ZEP layer. The material stack is then exposed under e-beam exposure and developed in the ZEP developer and the alkali developer CD-26 to create the grating region. The soak in the CD-26 is to create an undercut with the LOR as shown in Figure 3.1 (3). Silver was then evaporated using a thermal evaporator Figure 3.1 (4). The lift-off was completed by immersing the structure in CD 26 to remove the LOR. The standard resist remover, Remover PG, could not be used because the lower level of ZEP must remain. After the top two layers (ZEP/LOR) were lifted off, a second, aligned e-beam exposure and resist development defined the polymer waveguides. The last step of the process was to spin-coat the OG-603 adhesive as the top cladding material.

To our knowledge, this is the first demonstration of a four-layer lift-off procedure. Unlike a bi-layer system, this process is suitable for fabricating metallic patterns embedded in polymer. In the following sections, we will provide some details on the fabrication process.
3.2 Multi-Layer Coating

The devices described in this work were fabricated on Si substrates. The adhesive (OG-603), which works as cladding material, was first spin coated at 3500 rotations per minute (rpm) for 60 s on the substrate and then cured for 60 s using UV light in a nitrogen (N₂)-filled box. The coating did not cure well in air since OG-603 had free radical initiators, and oxygen prevented the polymerization reaction from completion. Since the viscosity of OG-603 was high, it was hard to coat thick layer at low spin speed. To achieve a thick lower cladding, we used three spin-coating steps to achieve a final thickness of about 8 μm. That the film was then baked for 5
hours around its glass transition (80 °C) in an oven to further improve the physical properties of the adhesive layer.

The ZEP was deposited on the OG603 in a standard way. A 500 nm thick ZEP 520A layer was spin-coated at a speed of 3500 rpm on the adhesive layer and pre-baked in an oven at 180 °C for 30 min.

Next, an 80 nm thick LOR was coated immediately on the ZEP and baked at 170 °C for 30 min in the oven. In this step, several factors should be well controlled. First, acceleration should be chosen carefully. Since the resist begins to dry in the few seconds of the process, it was important to accelerate the substrate to the final spin speed quickly. We usually chose an acceleration time to be 3~5 s for LOR. The layer was then pre-baked in an oven. The gradual heating provided by the oven was essential in limiting the formation of cracks in the polymer layers. We found that higher bake temperatures and longer bake times made the LOR film removal more difficult and produced a lower undercut rate, which is confirmed by Figure 3.2 from the manufacturer of the LOR. As mentioned above, since CD-26 was used to wash away the LOR layer and OG-603 was not resistant to CD-26 beyond several hours, a relative high LOR undercut rate was desired.

Finally, the last top ZEP layer was coated at 6000 rpm and baked in oven at 180 °C for 30 min. The top ZEP layer worked as pattern mask during the lift-off process, so it could be kept thin. We used a diluted ZEP resist (ZEP520A:Anisol ~ 1:3) to deposit the thin top layer. Since there was more solvent in the diluted ZEP resist, the diluted ZEP resist evaporated faster than the normal ZEP resist and a high acceleration rate was selected to prevent deformation and cracks in the films.
Figure 3.2 Undercut rate of LOR 2A resist using LDD26W developer, from the manufacturer.

Figure 3.3 L-Edit layout of the designed exposed patterns.

Figure 3.4 Layout of single waveguide pattern design.
3.3 E-beam Exposure and Development

We used e-beam exposure to define the device in ZEP. The structure needed to be e-beam exposed twice – the first time for the grating, and the second for the polymer waveguide. A markers system was introduced for the aligned exposure steps. First, the grating pattern of the ZEP layers was written using a Vistec EBPG 5000+ e-beam writer system at 100 kV. The e-beam exposed top ZEP resist was developed by ZED N50 at room temperature for 30 s. followed by rinsing in MIBK: IPA (9:1) for 30s and N₂ gas blow dry.

The L-Edit design of the exposed patterns is shown in Figure 3.3. There were six groups of waveguides. In each group, the patterns included seven waveguides that were 6 mm long. The length of the metallic grating structure was chosen to be 5, 7, 10, 15, 20, 30 and 70 μm. An extra waveguide without grating structure worked as a reference in the second and fifth groups counting from the left. The separation between two waveguides was 250 μm. 12 marks were designed around each group of the patterns for alignment. The design for a single waveguide is shown in Figure 3.4. The yellow regions are exposed during the first exposure. The grating in the center is the pattern for our device. The outside large yellow rectangles were exposed and deposited with metal to define the lift-off region. The region between these two rectangles was around 25μm. This area is smaller than the area outside the rectangles. Therefore, the lift-off in this central area is easier and faster than other areas. In this way, we can decrease the time of...
lift-off process. The central waveguide (grey region) is written during the next exposure. A microscope image of the first exposure is shown in Figure 3.5. In the second e-beam exposure, the first three groups of patterns from left were exposed separately by using the inside markers and the last three groups were exposed at the same time by using the outside markers. In this way, we could test how the markers affect the alignment accuracy.

In the [40], it was reported that since the high concentration of CD-26 resulted in a large undercut so the overhang could collapse, CD-26 with concentration of 60% was recommended to be the best concentration to dissolve the LOR layer. Therefore, during the development, the LOR was dissolved in the developer CD-26 with a concentration of 60% for 120 s, and then rinsed in de-ionized water. The sample was blow dried by compressed nitrogen gas. Since LOR was insensitive to e-beam exposure, isotropic dissolution rate in alkali chemicals led to an undercut profile beneath the top ZEP layer. The bottom ZEP layer was developed in ZED N50. The development time was extended to 60 s because of the thicker layer (500nm), followed by rinsing in MIBK: IPA (9:1) solvent and blow drying.

3.4 Metallization and Lift-off

The metallic features were formed by thermal evaporation. 500 nm thick silver was deposited on the top of the sample by thermal evaporation. The deposition rate was well controlled to improve the quality of the grating structure. To wash away unpatterned ZEP520 and LOR resist, the sample was placed into CD26 solvent for three hours and then in an ultrasonic bath for 5 min to improve the lift-off efficiency. Since the cladding layer could not tolerate CD26 for long time, the high dissolute rate was required. In this step, a high concentration (100%) of CD26 was used as the remover of LOR resist layer. Subsequently, de-ionized water was applied for rinse and clean. After dissolution of LOR, the metallic grating buried in the bottom ZEP resist layer remained.
3.5 Second E-beam Exposure and Alignment

Finally, a second e-beam exposure was performed to pattern the waveguide. In this step, alignment was necessary to overlap the patterns written during two e-beam exposures. The alignment markers were written with the grating pattern during the first exposure and created at the same time during the metallization of silver. This approach simplified the fabrication process but made it hard for e-beam writer to find markers possibly because the epoxy substrate was not sufficiently flat and because silver generated a smaller reflection signal than gold. The position of the markers also affected the accuracy of the alignment. The farther the markers were away from patterns, the higher error the alignment had. Therefore, the distance between markers should be less than 2 mm for the alignment to be successful. Figure 3.6 (a) shows the alignment results by using markers that were around the entire patterns (separation about 6 mm), and Figure 3.6 (b) shows the results using the markers around one group of designed waveguides, between which the distance was much shorter (~1.7 mm). The alignment shown in (b) was much better than that shown in (a). Finally, ZED N50 was used to develop the exposed bottom ZEP layer for 60 sec, followed by a rinse in MIBK: IPA (9:1) and blow dry by compressed nitrogen gas.

Figure 3.6, (a) Alignment results by using outside markers. (b) Alignment results by using inside markers
3.6 Heater

To change the refractive index of the polymer, we used the thermo-optical effect of the polymer. A localized heater would provide the temperature control to achieve modulation. According to Joule’s law, current flowing through a conductor generates heat. Thus, to build a localized heater, we adhered a thin cooper wire on the surface using an epoxy adhesive. The microscope picture of the heater is illustrated in Figure 3.8. The diameter of the wire was approximately 0.08mm. The disadvantage of this method was that the diameter of the wire was wider than the device area, so it was difficult to determine the temperature on the active area. As alternative, we also considered making a heater by adding an extra patterned metal layer during the fabrication. However, that meant one more lift-off process and alignment procedure, which made the fabrication more complicated. The extra lift-off process may increase the probability of damaging the device.

Figure 3.7, Optical microscope image of localized heater.

3.7 Summary of Fabrication Process

The fabrication process of the device is summarized in the steps below:
1. Layer 1: (Spin coating OG603, 3500rpm, 60 s, UV cure 60 s). Repeat 3 times.
2. Bake in oven at 95C, 5 hours.
3. Layer 2: Spin coating ZEP 520A, 3500rpm, 60 s.
4. Bake in oven, 180C, 30 minutes.
5. Layer 3: Spin coating LOR 1A, 6000rpm, 20 sec.
8. Bake in oven, 180C, 30 minutes.
9. Expose: Dose: 870 $\mu$C/cm$^2$ @ 100 KeV.
10. Development: For ZEP 520 3A : ZED-N50 for 30 sec
     :MIBK:IPA=9:1 (volume) for 60 sec.
     For LOR 1A : CD26: DI H2O=6:4 for 2 mins
     DI H2O for 2 mins.
     For ZEP 520A: ZED-N50 for 90 sec
     :MIBK:IPA=9:1 (volume) for 60 sec.
11 Metallization: silver, 500 nm, ~3A/s.
12. Lift-off: CD26 (100%) for 3 hours.
13. Expose: Dose: 270 $\mu$C/cm$^2$ @ 100 KeV.
     :MIBK:IPA=9:1 (volume) for 60 sec.
15. Spin coating OG603, 3500rpm, 60 sec, UV cure 60sec.
16. Adhere metal wire for heater.
4.1 Calibration of the Heater

The first step in our measurements is to calibrate the heater. In our experiment, it is much easier to measure the current than to directly measure the temperature. As long as the relationship between the current and temperature is known, we can use the current instead of temperature to specify the modulation properties of the device. The resistance of the heater was measured to be around 3 $\Omega$. During the temperature calibration, at each current setting we waited for 1 to 2 minutes for the temperature to settle before we measured it using a Accu-Temp digital thermometer. Figure 4.1 shows the plot of the measured temperature versus current for the wire heater.

The temperature can also be estimated using Joule's law. The increased temperature $\Delta T$ for heating time $t$ is given by:

$$\Delta T = \frac{I^2 R t}{C_p L A D}$$  \hspace{1cm} [4.1]

where $I$ is current, $R$ resistance of the heater, $C_p$ the heat capacity of copper, $L$ is the total length of the wire, which was about 25 cm, $A$ is the cross section area of the wire which can be obtained from the diameter (0.08 mm), and $D$ is the density of copper. When current was 0.2 A, the
measured temperature was 24°C, but the result of calculation using Eq. 4.1 was 152°C, which was much greater than the measured datum. However, Equation [4.1] gives the temperature of copper wire itself and not of the polymer. The wire on the top of the chip was covered by epoxy. Therefore, during the calibration, the tip of the thermometer was placed on the top of the polymer surface. Since both epoxy and air are not good thermal conductors (thermal conductivities of epoxy and air are around 0.3 and 0.025), the heat was well isolated by the epoxy and air. Another reason for the discrepancy may be that the temperature measured by the thermometer was the average of the tip area of the thermal probe. Since our sample was quite small relative to the thermal probe, only a small area of tip touched the sample and other areas were exposed to the air. Thus, the measured temperature was the average of the sample surface temperature and the background temperature. Finally, the Eq. 4.1 could not accurately describe the temperature on the chip.

To describe this process precisely, the heat equation \( \frac{\partial T}{\partial t} = \alpha \Delta T + Q', \) where \( \alpha \) is a positive constant and \( \Delta \) is the Laplacian operator) should be solved to obtain the distribution of temperature in a given region over time. In this work, we did not solve the heat equation. However, we could calculate the temperature gradient at thermal equilibrium. Fourier’s law establishes the relationship between the time rate of the heat transfer and the gradient the temperature, which is

\[
\frac{\Delta Q}{\Delta t} = -kA \frac{\Delta T}{\Delta x}. 
\]  

[4.2]

where \( \Delta Q/\Delta t \) is the amount of heat transferred per unit time, \( k \) is material conductivity, \( A \) is the cross-sectional area, \( \Delta T \) is temperature between two ends, and \( \Delta x \) is the separation between the two ends. When the sample reached thermal equilibrium, all of the generated heat by the current was transferred. The amount of transferred heat should equal to the amount of generated heat, \( \Delta Q/\Delta t = I^2R \). So,

\[
I^2R = -kA \frac{\Delta T}{\Delta x}. 
\]  

[4.3]

Using this equation, we can find the different of temperature between top and bottom of cladding
layer. The calculated results were shown in table 4.1. When the current was small, the temperature difference was low relative to the temperature of top surface so that it could be neglected. However, as the current increased, the temperature difference increased.

<table>
<thead>
<tr>
<th>I (A)</th>
<th>Temperature difference between the top and bottom cladding layers calculated from Fourier’s Law.</th>
<th>Temperature measured on the top of cladding layer.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>1.3 °C</td>
<td>24°C</td>
</tr>
<tr>
<td>0.4</td>
<td>5.14 °C</td>
<td>42°C</td>
</tr>
<tr>
<td>0.6</td>
<td>11.6 °C</td>
<td>66°C</td>
</tr>
<tr>
<td>0.8</td>
<td>20 °C</td>
<td>112 °C</td>
</tr>
</tbody>
</table>

Table 4.1 Calculated temperature difference between top and bottom of cladding layer.

Figure 4.1, Plot of temperature versus current.
4.2 Transmission Measurement

4.2.1 Experimental Setup.

Figure 4.2 Schematic diagram of experimental setup for intensity measurement.

Figure 4.2 shows our schematic diagram of the experimental configuration. The laser light source we used was tunable in the wavelength range of 1.52~1.62μm. A polarization controller selected the input polarization. The laser beam was fiber-coupled into the device under measurement. The transmitted light is coupled out from device chip by using a 20x objective lens. After propagating through a polarizer, the light is observed by an infrared camera system. The reason of using camera as a detector will be discussed in the next section. A DC power supply connected the localized heater to drive the current through the wire heater. During the experiment, we first coupled the light into the reference waveguide and set the output polarizer to the expected polarization (TM or TE), then adjusted the polarization controller to maximize output. By this way, we can pre-set the polarization of the light allowed to pass through the waveguide. Then, we measured the transmissions under the different temperatures.
4.2.2 Measurement Results

On the chip, we built several waveguides with metallic structures that have different lengths. A waveguide without metallic structure was also made as a reference waveguide. The mode profiles of the waveguides with and without metallic structure were first observed. A typical mode profile of the reference waveguide is shown in the Figure 4.3 (b).

Figure 4.3, (a) The cross section of the device. TE mode profile of the reference waveguide when (b) I=0 and (c) I=0.8A.

The dark spot in the center was the guided mode. The smaller dark spot on the bottom was regarded as cladding mode that propagated in the bottom cladding layer. Since the thickness of the bottom layer was about 8μm, the distance between center point of the central spot and the top edge of the bottom spot, labeled by $d$ in Figure 4.3, is around 8μm. Therefore, the gap between two spots, labeled by $dg$, is only approximately 2~3μm. A single-mode fiber usually has a core diameter around 9μm. Therefore, if a single-mode fiber was used to collect light, it could not distinguish between the guided mode (center) and the cladding mode (bottom). Thus, all the measured data was collected using an IR camera.
From the guided mode profiles under different temperatures we observed that the spatial profiles of the modes spread out as the temperature increased. Figure 4.3 (b) shows the profile of the fundamental TE mode of the reference waveguide with zero current passing through the heater. As shown in Figure 4.3 (c), when the current was increased to 0.8 A, long tails became longer on both sides of the mode profile. This phenomenon indicates the optical confinement decreases with increasing temperature. Since the cladding has a negative thermo-optical coefficient, the decreased confinement meant that the index of the core dropped faster than that of the cladding material as the temperature increased.

To evaluate the change in index contrast due to the thermo-optical effect, we estimate the amount of spread of the mode profile. The cross sections of the measured mode profiles were shown in Figure 4.4 (a). The black dash line denotes the original mode profile when the current was I=0 and the red curve denotes the spread mode profile when the current was I=0.8A. The total width of the mode profile increased by 30% when I was increased to 0.8 A. By corroborating the measurements with mode calculations, we found that the change from 1.535 to 1.522 in the index of ZEP (core material of the waveguide) dominated the mode spread effect due to decrease of the index contrast. Therefore, 0.8 A current passing through the heater leads to a change of 0.013 in refractive index of the ZEP. The COMSOL simulation data was shown in Figure 4.4 (b). The black dash line denotes the original mode profile and the red curve denotes
the spread mode profile when the refractive index of core is changed from 1.535 to 1.522.

Figure 4.5, Plots of normalized transmission versus current for (a) TE modes and (b) TM modes of reference waveguide and metallic devices with lengths of 7μm and 15μm.

Figure 4.6, Plots of absolute transmission versus current for (a) TE modes and (b) TM modes of reference waveguide and metallic devices with lengths of 7μm and 15μm.

We measured the transmission of the TE and TM modes of the waveguide with the metallic structures. As a reference, the transmission of the reference waveguide with change of temperature was also measured. The measured intensity data was the integral over the area of the mode spot in the camera pictures. Figure 4.5 (a) and Figure 4.5 (b) show the TE and TM transmission, respectively, as a function of the current at a wavelength of 1520 nm for different lengths of the metallic grating structure. From these figures, we observed the sudden
transmission dropped at high current. However, the same cut-off was also observed to take place even in the reference waveguide. Furthermore, regardless of the length of the metallic structures, the transmission curves dropped almost at the same rate. In our original design, the transmission curve for longer devices should drop faster than that for the shorter device. The drop in the transmission occurred for both polarizations. Also, the extinction ratios for TE and TM light were similar, at around 1.4 dB and 0.9 dB, respectively. These features indicated that the cut-off was less dependent on polarization and not a consequence of the metallic structures as predicted in Chapter 2. We believe this cut-off behavior can be attributed solely to the polymer waveguide. However, the low extinction ratio does not make the waveguide efficient for amplitude modulation.

The plots of measured absolute TE and TM transmissions versus current at $\lambda=1520\,nm$ for different lengths of the metal structure are shown in the Figure 4.6. The higher losses were observed in longer lengths of the metal structure, which indicated that the observed losses were associated with absorption of the metal. From the measured data, the propagation loss in the metal structure for TE mode was estimated to be approximately -1.0dB/μm, which was close to the prediction from the simulations (~ -1.4dB/μm). In contrast, the observed TM propagation loss in the metal structure, which was around -0.37dB/μm, was significantly higher than the simulation result (~ -0.02dB/μm). Such observation was likely due to the roughness of the metal surfaces. Since the field of the TM mode was strongly confined on the metal-dielectric interface, the TM mode properties were easier to be affected by the quality of the metal surface than TE mode.

To further discover the properties of the device, we measured the transmission at several wavelengths for TE light. The results for the reference waveguide and the devices with lengths of 7μm and 15μm are shown in the Fig 4.7 (a), (b) and (c), respectively. The transmission was essentially wavelength independent.
Figure 4.7, Plots of normalized transmission versus current for TE modes of (a) reference waveguide, (b) device with a length of 7μm, and (c) device with a length of 15μm at different wavelengths labeled in the figures.

4.3 Group Indices Measurement

4.3.1 Principle of Measurement.

According to the theory of a Fabry-Perot resonator, the transmission $T$ as a function of wavelength $\lambda$ is given by

$$T = C \frac{e^{-\alpha L}}{1 + R^2 e^{-2\alpha L} - 2 e^{-\alpha L} \cos \frac{4\pi n L}{\lambda}}$$  \[4.4\]

where $\alpha$ labels the cavity internal loss, $n$ is the refractive index of filling material, $L$ is its length, $R$ is the mirror reflectivity and $C$ a scaling constant. In a typical plot of transmission spectrum, the maxima of the transmission occur with a period of

$$P = \frac{\lambda^2}{2L(n - \lambda \frac{dn}{d\lambda})}$$  \[4.5\]

The terms in the bracket in the denominator of Equation [4.5] are the group index ($n_g = n - \lambda \frac{dn}{d\lambda}$). Equation [4.5] indicates that if the length $L$ is known, we can obtain the
group index when the period $P$ is measured by scanning the wavelength. If the resonator is formed by the waveguide, the effective group index of the guided mode, instead of the group index, will be determined.

Suppose that the metallic structure forms a resonator, according to equation [4.5], we can estimate the period for the metallic structures with different device lengths at a wavelength of 1550 nm as displayed in the Table 4.2. The period is shorter for a longer device length. Since the wavelength range of our tunable laser is from 1520 nm to 1620 nm, we have to choose the proper device length so the measured period lies in the range of our laser source. To find the difference between two group indices, we measured the difference between the two periods corresponding to two group indices. The change in the period can be evaluated by taking the derivative on the both sides of the period equation:

$$\Delta P = \frac{\lambda^2}{2L} \Delta n_g.$$  \hspace{1cm} [4.6]

$\Delta n_g$ is approximately equal to 0.013, which was estimated by the spread in the mode profile, and we take $n_g \sim 1.5$. The calculated results of $\Delta P$ are illustrated in Table 4.2. $\Delta P$ decreases as the device length increases. To complete the group index measurements, the period, $P$, should be short, and $\Delta P$ should be large. By trading off these two issues, we chose a device with length of 10μm to measure the group indices.

<table>
<thead>
<tr>
<th>$L$ (μm)</th>
<th>$P$ (nm)</th>
<th>$\Delta P$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>107</td>
<td>1.49</td>
</tr>
<tr>
<td>10</td>
<td>75</td>
<td>1.04</td>
</tr>
<tr>
<td>20</td>
<td>37.5</td>
<td>0.52</td>
</tr>
<tr>
<td>30</td>
<td>25</td>
<td>0.35</td>
</tr>
<tr>
<td>70</td>
<td>10</td>
<td>0.15</td>
</tr>
<tr>
<td>1000</td>
<td>0.75</td>
<td>1.04x10^{-2}</td>
</tr>
</tbody>
</table>

Table 4.2, Calculated periods $P$ and $\Delta P$ for devices with different lengths.
4.3.2 Experimental Setup and Measurement Results.

![Figure 4.8 Schematic of the experimental setup for the group index measurement.](image)

The experimental arrangement is shown schematically in Figure 4.8. The input part of the setup is same as what we used in the previous transmission measurement. However, a single-mode fiber and a power detector replaced the objective lens and the infrared camera to couple the light out and to detect the light intensity. As shown in Table 4.2, the change in the period was 1.04 nm for 10μm long device. The increment in the wavelength scan must be smaller than 1.04 nm so that the difference in the measured periods could be distinguished. High resolution of wavelength leads to hundreds of data points for each scan. We programmed the wavelength scan and data collection.

In the measurements, we found the two edges of the chip also formed a resonator. The length of the chip was about 1 cm, which resulted in a period of 0.075 nm. This value is 1000 times smaller than our period of interest (75 nm). Therefore, we expect to see a fast varying curve superposition with a slow varying curve, and two curves with these two periods should not affect each other. The TE and TM modes for 10μm long device were measured at various currents by the present method. The results are shown in Figures 4.9 and 4.10. To extract the period from measured results, a nonlinear fitting process was performed by using a fitting function based on
the Fabry-Perot transmission function given by

\[ \frac{C \cdot G}{1 + (RG)^2 - 2RG \cos(\frac{4\pi nL}{\lambda})} \cdot e^{-\beta \lambda} \]  \[ [4.7] \]

where \( C \) is a constant, \( G \) represents a attenuation term that equals \( e^{-\alpha \lambda} \), and \( R \) is the cavity reflectivity. The last exponential term was introduced to compensate the power drift during the measurement. The fitting parameters are \( C, R, G, n, \) and \( \beta \). To ensure the physical results, parameters \( R \) and \( G \) were forced to be less than 1 during the fitting process. The fitting curves in all these figures are shown as green lines. After the fitting curves were obtained, the fitting parameter \( n \) itself directly represents the effective index. We also can calculate the group index by finding the wavelengths \( (\lambda_1, \lambda_2) \) of two neighboring maxima (or minima) that are labeled by red point in the fitting curve figures. If it is assumed that the dispersion of the material varies slowly, the effective group index is given by

\[ n_g = \frac{\lambda_1 \lambda_2}{2L(\lambda_1 - \lambda_2)} \]  \[ [4.8] \]

where \( L = 10\mu m \).

Figure 4.9, Plots of TM normalized transmission intensity versus wavelength when (a) \( I=0. \) and (b) \( I=0.8A. \)
Figure 4.10, Plots of TE normalized transmission intensity versus wavelength when (a) I=0.
and (b) I=0.8A.

Figures 4.9 (a) and (b) are the normalized TM transmission spectra when the heater current
was I=0 and I=0.8A, respectively. The fitting parameter n for I=0 case was equal to 1.5246 ±
0.001, which is close to the COMSOL simulation result of 1.5212. The group index from the
fitting curve was 1.5196. In the case of I=0.8A, the data is best fitted with the parameter n of
1.4935 ± 0.0008. The calculated group index is 1.4834.

The TE mode data measured with zero heating current is shown in Figure 4.10 (a). The
fitting parameter n and group index n_g are obtained to be 1.4902 ± 0.001 and 1.4888, respectively.
When the current increase to 0.8A, effective index was fitted to be 1.4854 ± 0.001 and the group
index of 1.4747 was extracted from the fitting curve in Figure 4.10 (b).

The fitting results highly depended on the initial guess of a series of parameters. For
example, in the case of the data in Figure 4.9 (a), the fitting result of the n parameter varied from
1.51 to 1.56 when the different initial guess was used. The wide range of fitting results might be
due to the fact that only one period was observed in the wavelength range. Also, the measured
data did not show a strong resonance. The reflectivity on the interface between the waveguide
section and the metallic structure section was unpredictable so we were not sure whether the metallic structure in the waveguide could form a good Febry-Perot resonator. The metal material and the unsmoothed metal surface due to imperfect fabrication process made high losses in the metallic section.

The group indices from curve fitting were less than the corresponding fitting effective indices. However, according to the simulations, the effective index should be a mono-decreasing function of wavelength over our wavelength range. Therefore, the derivative of effective index with respect to the wavelength should be negative. By using the definition of group index \( n_g = n - \frac{\lambda}{\lambda} dn/d\lambda \), the group index should be greater than the effective index. These theoretical results were opposite to our experimental results. Since there were many uncertainties and inaccuracy in the experiment as discussed above, we had reasons to doubt the designed structure. Further improvements of the experiment will be discussed in the next and final chapter of this thesis.
Chapter 5

Conclusions and Future Works

5.1 Discussions and Conclusions

Summarizing the results of this thesis, we fabricated on-chip polymer waveguides with embedded metallic strips with the goal of achieving efficient polarization or intensity modulation. In Chapter 2, the Finite Element simulation (COMSOL) showed that TE mode cut-off as refractive index of the cladding material changed while the TM mode did not. This effect should, in principle, make possible a tunable polarization rotator with a short conversion length by using metallic grating structures. However, in Chapter 4, the measurements of the TE and TM transmission did not agree with these predictions. We observed that TE and TM cut-off at same time, which indicated that the cut-off was not due to the metallic structure, but probably due to the polymer waveguide itself. The experimental data did not provide evidence that the metallic grating structure operated as designed.

There are several reasons for and lessons from this project. First, there should have been a backup plan. In the simulation, since we thought the heater would be built on cladding layer and the cladding material would be heated up first, we assumed that the change in the refractive index of cladding would dominate over the core. However, in practice, the opposite was true,
and the index contrast became smaller as the temperature increased. Since the reality was opposite to the initial assumption, the device should perform in different way. This can be understood simply. The wave number is given by \( k^2 = k_x^2 + k_y^2 + \beta^2 \) the summation of the wave-vector components. If the index contrast increased, the confinement of the field increased, so \( k_x \) and \( k_y \) should increase. As a consequence, \( \beta \) would be reduced until it is cut-off. On the contrary, a decrease in the index contrast meant \( k_x \) and \( k_y \) would reduce, and \( \beta \) would therefore increase. In this case, the mode would not be cut-off and our device could not perform the modulation function as expected. We over-estimated the thermo-optic effect of the cladding material and neglected to come up with an alternative design in advance. The simulation parameters were deduced from reference papers of other epoxy resin which did not apply to the epoxy used. Contingent plans should have been considered in advance and back-up designs should have been included for the fabrication.

These mistakes should have been corrected if we have enough time. However, the fabrication took too long to complete to try a variety of alternative designs. The cladding material, OG 603, took longer than expected to determine how to process. Alternative materials could have been considered which may have saved some time, even though we did finally find a working recipe.

In the future, I will be more flexible in the research. The physical reality is often more complicated than theory and simulations, so it is important to adapt to changes and new information gathered from experiments and experimentation.
5.2 Future Works

Since we did not know the exact thermal-optical property of the cladding material, the index contrast changed in a different way from the original expectations. There are two ways to fix this problem. First, we can use other materials as core or cladding material. But this time, we must carefully test the properties of the alternative material before use it. For this design to work well, it must be confirmed that the refractive index of cladding should drop faster than that of the core as the temperature rises. However, selecting and testing the proper material is not easy, since it may take a long time to learn the properties of the new material and to find a right recipe for fabrication.

Since we are already familiar with the present epoxies as a result of this current work, it will be better to find a solution based on the current material. Instead of changing material, changing geometry of the design may be another option. As discussed in the last section, an increased index contrast between the core and cladding cuts off the TE mode. Since the current material system results in a decrease of the index contrast, we can re-design the period of the device to let it work in the opposite way. The device can be designed such that TE mode is cut-off when the heater current is zero. As the current increases, the cut-off disappears and TE mode passes through the device. By this way, we can also control the TE mode and the output polarization.

In the current design, we attempted to make use of thermal-optical effect of the polymer for light modulation. However, the thermal effect limits the modulation rate due to relative low response time. In future work, a semiconductor may replace the polymer. The advantage of using semiconductor (e.g. Si) is its electronic properties can realize electro-optical modulation. Bit rates of silicon based optical modulator have been demonstrated to exceed 10 Gb/s [41]. In crystalline silicon, the refractive index is changed owing to carrier density changes (either injection or depletion). Compared to polymer waveguides, the core refractive index of silicon waveguide is much higher (~3.4), so the cutoff period of metal grating embedded in silicon
waveguide will be much shorter than that in polymer waveguide. This will make the width of the waveguide more compact. Since the refractive index of core reduces with carrier injection, the device must be designed to work in opposite way discussed in last paragraph. However, due to the high refractive index of Si, the SPP mode suffers higher losses. according to the dispersion relation \( \beta = k_0 \sqrt{(\varepsilon_r \varepsilon_z)/(\varepsilon_r + \varepsilon_z)} \).

Also, the weak electro-optical property of Si (index change of \(10^{-3}\) with carrier density changes of \(10^{-3}\) cm\(^{-3}\)) will be a challenge of the silicon device design. The advantage of an electro-optic based semiconductor device is that the metal structure in the SPP device can also be used to carry the modulation electrical signal. These highly compact devices can be useful for dense electronic-optical integration.
References


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