TE/TM Pass Guided Wave Optical Polarizer

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Abstract

A metal-clad guided wave optical polarizer with a high-index dielectric buffer layer is analyzed. The TE and TM polarization characteristics of the infinitely long version of the polarizer are well-known and are easily obtainable by solving the Helmholtz equation. The infinitely long polarizer model does not account for the input/output ends of the polarizer and thus it is not practical. In this work, we analyze the finite-length version of the same polarizer using the Method of Lines. In this manner, we account simultaneously for the absorption loss due to the presence of the metal and the loss due to reflection at the input and output ends of the finite-length polarizer. The effect of the polarizer length and thickness of the high index buffer layer on the TE/TM discrimination properties of the polarizer are calculated by the MOL.

1 Introduction

Metals have very interesting and unique properties at optical frequencies. They are characterized by a complex dielectric constant that has a negative real part. Metals have found many applications in integrated optics. Some of them include for instance their use as optical isolators in order to protect optical elements from stray light [1], in heat sinking, as interconnects to active optical elements, in surface plasmon microscopy and in mode [2, 3] and polarization filtering [2, 4].

Polarization filters are important elements of integrated optical circuits having applications in signal processing from optical fiber sensors and in fiber optic gyroscopes. TE mode transmission can be achieved using metal-clad optical waveguides characterized by much larger TM mode absorption loss [5, 6]. Experimental work related to TE-pass polarizers has been reported in [7], [8] and [9]. TM-pass guided wave polarizers based on the discriminatory radiation of the TE and TM modes were reported in [10] and [11].

The simple three layer metal-clad optical waveguide (dielectric substrate-dielectric core-metal superstrate) are characterized by a much higher TM mode absorption loss compared to the TE modes [5, 12]. The inclusion of a low-index dielectric buffer layer of suitable thickness (with a smaller refractive index compared to the core) between the core and the metallic superstrate can enhance the TM mode absorption loss with respect to the TE modes, leading to an improved TE-pass polarizer [6]. This effect can be reversed by utilizing a high index (with respect to the core refractive index) buffer layer instead of the low-index layer [13]. If a suitable thickness of the high index buffer layer is used, this simple technique can effectively increase the TE attenuation compared to TM waves and we thus end up with a TM-pass polarizer. The infinitely long version of this polarizer has been reported in the past [13]. The effect of the high index buffer thickness on the TE and TM pass properties of the polarizer has been reported in that work.

In practice, a guided wave polarizer has a finite-length. The incident guided wave is reflected at the input and output ends of the polarizer. This reflection may modify the properties of the finite-length device profoundly. Effects such as loss due to radiation at the input and output ends as well as resonant cavity effects may arise in the case of the finite-length polarizer. In the present work, we will study the effect of the finite length of the polarizer on the TE/TM polarization properties. The well-known Method of Lines (MOL) will be used for this purpose [14].

The MOL is a semi-analytical method used in the solution of partial differential equations [15]. The dependent variable (in our case, the electromagnetic field) is discretized in all spatial directions, except one. It is solved analytically in that remaining direction. This hybrid method has the advantage of enhanced accuracy and efficiency compared to fully discretizing techniques [16, 17]. It can be used to account for wave reflection and transmission at a single and multiple longitudinal discontinuities. The reader is referred to the literature for more details of this powerful numerical method [16, 17].

2 Effect of the High-Index Buffer Layer

Figure 1 shows a four layer metal-clad slab optical waveguide using a high-index layer that separates the core region from the metallic cladding (superstrate). The metal is assumed to be gold which has a refractive index of $n_m = 0.1804 + j10.2$ ($\epsilon_r = n^2 = -104 + j3.68$) at the operating wavelength $\lambda = 1.55\mu m$. The core thickness is fixed at $4\mu m$ and the thickness of the high index buffer layer b is varied in order to control the TE/TM discrimination properties of this waveguide. The core thickness of $4\mu m$ is chosen so that when $b = 0$, the waveguide supports only the TE_0 and TM_0 modes. The guided optical modes of this waveguide are known to be lossy and are characterized by complex effective indices, which may be expressed as ($n_{eff} = n_{eff}' + jn_{eff}''$), where n_{eff}' and n_{eff}'' are respectively, the real and imaginary parts of the complex effective index. In the absence of the high index buffer layer ($b = 0$), the TE_0 mode has much small absorption loss compared to the TM_0 mode (i.e. ${n_{eff,TM_0}}'' >> {n_{eff,TE_0}}''$). This obviously leads to higher attenuation of the TM_0 mode compared to the TE_0 mode and thus we have the basis of a TE-pass polarizer. The modal propagation constant β and effective index are related by $\beta = k_0 n_{eff}$, where $k_0 = 2\pi/\lambda$ is the free space wave number. The complex propagation constant may be written as $\beta = \beta' + j\beta''$. The modal attenuation constant β'' is used in the calculation of the modal power loss. Table 1 shows the calculated complex effective index and power loss in dB/cm for each of the supported modes. Clearly, the TM_0 power loss of approximately 51 dB/cm is much higher than the TE_0 power loss, which is less than 1 dB/cm.

When the high index buffer layer is introduced between the core and metallic superstrate ($b > 0$), the modal characteristics are modified. In particular, for certain values of the parameter, b, the relative loss of the TE and TM waves is reversed, leading to enhanced attenuation of the TE_0 mode compared to the TM_0 mode. In this case, we have the basis of a TM-pass polarizer. The effect of the buffer layer thickness b on the imaginary part of the propagation constant of the TE and TM modes is shown in figure 2. In this figure, it is clearly seen that for $b = 0$, ${\beta_{eff,TM_0}}'' >> {\beta_{eff,TE_0}}''$. However, as b increases above the value of zero, the loss of the TE_0 mode increases while simultaneously, the loss of the TM_0 mode decreases. The loss of the two modes become equal at about $b = 0.13\mu m$. Beyond this point, the TE_0 mode become more lossy than the TM_0 mode. The TM_0 mode has minimum loss in the approximate range $b = 0.15 - 0.20\mu m$. This range is favorable so that the four layer waveguide operates as a TM-pass polarizer. Note that the TE_1 become supported above $b \approx 0.17\mu m$. Thus, in the absence of the high-index layer, TE polarized waves have low loss compared with TM polarized waves. The situation is effectively reversed when a high-index buffer layer of suitable thickness (in the present case, $b = 0.17 - 0.20\mu m$) is introduced.

The above discussion is based on an infinitely long version of the slab waveguide. This model does not account for the finite-length of the device. The infinite model is not practical, because it does not account for wave reflection at the input/output ends of the finite length version. Wave interference due to the resulting cavity effect is also not accounted for using the infinite model. For these reasons, we will study the effect of the finite-length of the polarizer for both the TE-pass and the TM-pass cases.

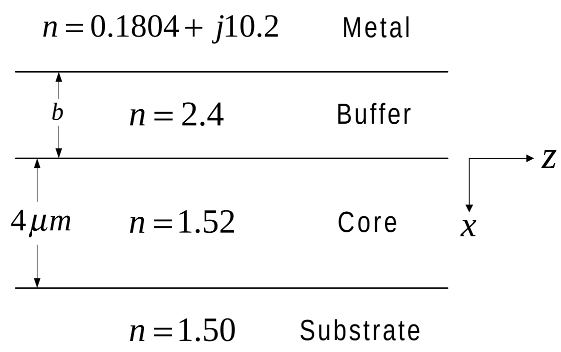

Figure 1: Metal-Clad Waveguide with a High-Index Buffer Layer

Mode	n_{eff}'	n_{eff}''	Power Loss (dB/cm)
TE_0	1.51241	2.37701e-6	0.837
TM_0	1.50818	144.93140e-6	51.030

Table 1: n_{eff}', n_{eff}'' and Power Loss of the supported TE and TM modes for a Metal-Clad Waveguide without a Buffer Layer at $\lambda = 1.55\mu m$

3 The Finite-Length TE-Pass Polarizer

The finite-length TE-pass polarizer is shown in figure 3. The device has a finite-length L and occupies the longitudinal range ($0 \leq z \leq L$). The thickness of gold is assumed to be $0.5\mu m$. The TE_0 mode or the TM_0 mode is assumed to be incident from the left ($z \leq 0$). The optical field is scattered at the input and output ends of the polarizer. Part of the scattered

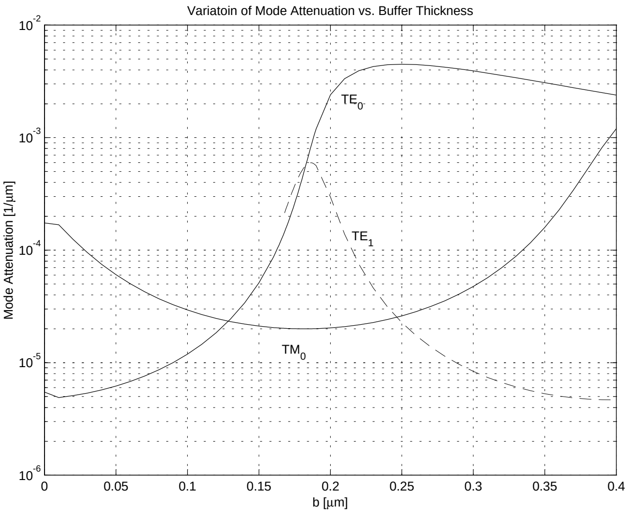

Figure 2: Variation of Mode Attenuation (β'') vs. Buffer Layer Thickness (b)

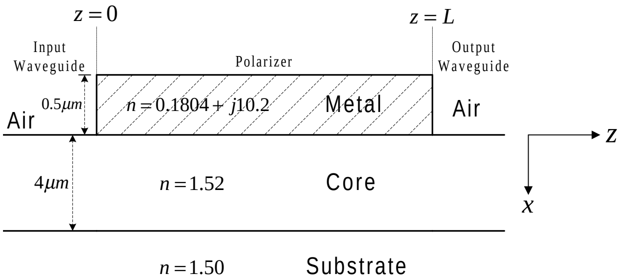

Figure 3: TE-Pass Polarizer

field is coupled to radiation modes and thus lost and part remains guided by coupling to guided waves. The extinction ratio (PER) is defined as the ratio of power remaining (at the output end) in the TE_0 mode (P_{TE_0}) to the power remaining (at the output end) in the TM_0 mode (P_{TM_0}) [9], expressed in decibels. In addition, the insertion loss (PIL) is defined as the power loss associated with the TE_0 mode. Thus:

$$PER = 10\ log_{10} \left(\frac{P_{TE_0}}{P_{TM_0}} \right) \quad (1)$$

$$PER = TE_0\ Loss\ in\ dB - TM_0\ Loss\ in\ dB \quad (2)$$

$$PIL = 10\ log_{10}\ (P_{TE_0}) \quad (3)$$

$$PIL = TE_0\ Loss\ in\ dB \quad (4)$$

The above equations assume that the input TE_0 mode has unit power at the input end of the polarizer.

In order to have a good TE-pass polarizer, we require the power remaining in the desired TE_0 mode at the output end of the polarizer to be as high as possible. Hence a *low* value of PIL is desirable. The effectiveness of the polarizer in discriminating against the passage of the TM_0 mode relative to the TE_0 mode is measured by the PER parameter. Thus, this parameter should be as *high* as possible. Hence, we require a high PER and simultaneously a low PIL. These two requirements can be contradictory in some cases and in such cases, a compromise has to be accepted in order to determined a suitable optimum length of the polarizer, $L_{optimum}$.

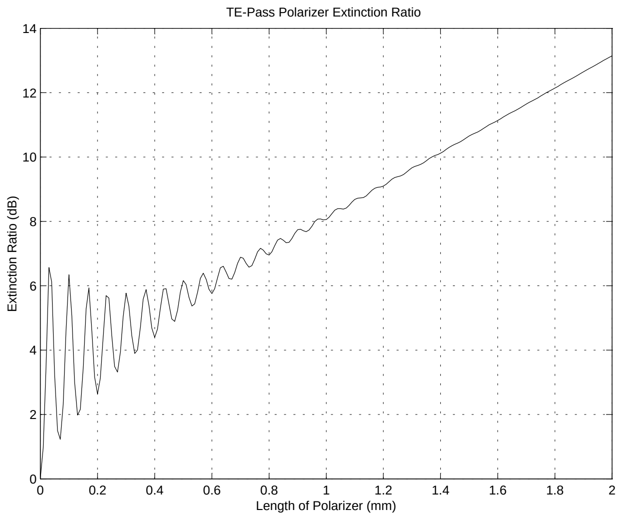

Figure 4: TE-Pass Polarizer Extinction Ratio

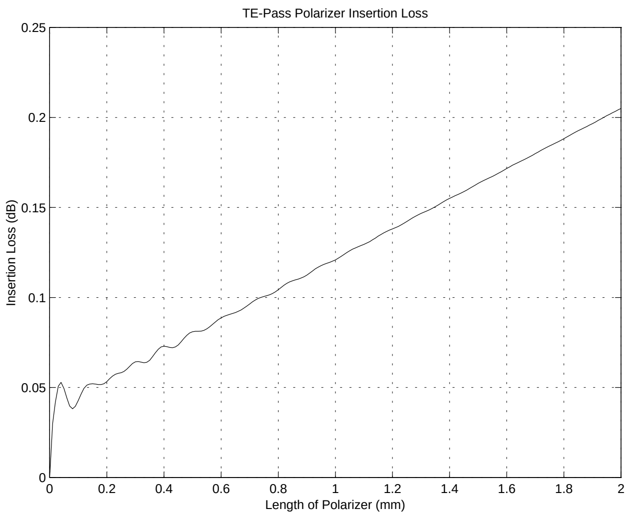

Figure 5: TE-Pass Polarizer Insertion Loss

Figures 4 and 5, respectively show the variation of the PER and the PIL of the TE_0-pass polarizer with L. Both of those parameters are characterized by initial oscillatory behavior. This oscillatory behavior is stronger in the case of the PER as compared to the PIL case. The oscillations are due to wave interference resulting from the cavity effect formed by

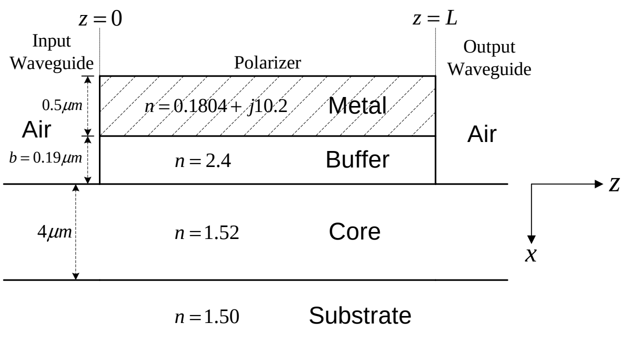

Figure 6: TM-Pass Polarizer

the input and output ends of the polarizer. When the device length increases, the interference pattern effectively disappears due to the increased round trip total attenuation of the guided wave. By examining figures 4 and 5, it is possible to select an optimum device length using small values of L. For instance, at $L = 23\mu m (L = 0.023mm)$, the PER has the first maximum value, with a value slightly larger than 6 dB and a corresponding very small value of $PIL = 0.05dB$. In some cases however, a larger value of PER is required. In that case, a long device length may be chosen.

4 The Finite-Length TM-Pass Polarizer

Figure 6 shows the four-layer TM-pass polarizer with a high index dielectric buffer of thickness $b = 0.19\mu m$ added to the previous three-layer TE-pass polarizer. The extinction ratio (PER) in this case is defined as the ratio of power remaining in the TM_0 mode (P_{TM_0}) to the power remaining in the TE_0 mode (P_{TE_0}) [9], expressed in decibels. In addition, the insertion loss (PIL) is defined in this case as the power loss associated with the TM_0 mode (assuming the input power of the input TM_0 mode is unity). Thus:

$$PER = 10\ log_{10} \left(\frac{P_{TM_0}}{P_{TE_0}} \right) \quad (5)$$

$$PER = TM_0\ Loss\ in\ dB - TE_0\ Loss\ in\ dB \quad (6)$$

$$PIL = 10\ log_{10}\ (P_{TM_0}) \quad (7)$$

$$PIL = TM_0\ Loss\ in\ dB \quad (8)$$

Figures 7 and 8 respectively show the variation of the PER and the corresponding PIL for a buffer thickness $b = 0.190\mu m$. High PER and low PIL are required in order to have a good TM-pass polarizer in this case. The oscillatory behavior of the PER with the polarizer length L has a much larger dynamic range than the previously considered TE-pass polarizer. This is

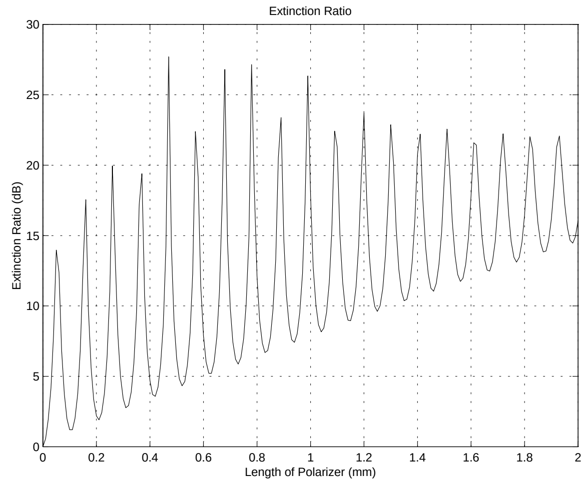

Figure 7: TM-Pass Polarizer Extinction Ratio for b=0.190 μm

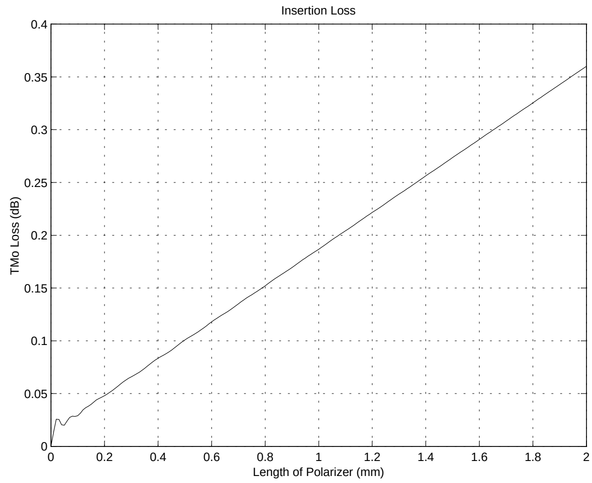

Figure 8: TM-Pass Polarizer Insertion Loss for b=0.190 μm

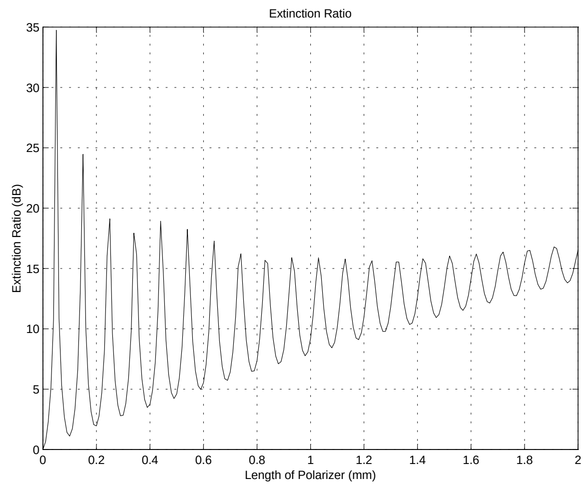

Figure 9: TM-Pass Polarizer Extinction Ratio for b=0.192 μm

probably due to the fact that the TE_0 mode experiences larger reflection at the input and output ends of the TM-pass polarizer considered in this case. This very high dynamic range can be advantageously used to obtain a TM-pass polarizer having a short length. For instance, as indicated in figure 7, a polarizer length $L \approx 0.45mm$ has a high PER of approximately 27 dB. The corresponding PIL has a very small value of approximately 0.1 dB, as seen in figure 8.

The buffer layer thickness b strongly influences the PER variation with L, which may be used to tune the device behavior. This is illustrated in figure 9 which shows the variation of the PER with L when the buffer layer thickness b is increased by a small amount ($b = 0.190\mu m$). The resulting PER curve in this case has a peak value of approximately 35 dB corresponding to the short device length $L \approx 0.05mm$ and the very small PIL of approximately 0.025 dB.

5 Conclusion

The finite-length metal-clad three-layer TE-pass polarizer and the finite-length four-layer TM-pass polarizer were analyzed in this work using the MOL. Both polarizer types are characterized by a PER curve that is an oscillatory function of the device length L. This oscillatory behavior can be used to obtain an optimized device length. For the TM-pass polarizer, the enhanced dynamic range of the PER variation and the possibility of tuning the PER by varying the high index buffer layer thickness can lead to short device length having a high PER and a very small PIL.

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