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Analysis of Silicon Clad Optical Waveguide for High Extinction Ratio TE/TM Pass Polarizers using Resonant Coupling between Guided Modes and Lossy Modes

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Abstract: *Attenuation characteristics of a planar silicon-clad ion exchange glass waveguide structure are investigated theoretically at the optical wavelength of 0.6328 µm. An oscillatory behaviour of the attenuation curves is noticed in the proposed four layer structure. It is observed that by varying the thickness of silicon cladding layer, the TE or TM propagating modes may be selectively attenuated. This characteristic can be used to design a high extinction ratio and low insertion loss TE or TM pass polarizer. For the analysis of both polarizations, effective indices are calculated at various thicknesses of Silicon cladding layer using Transfer Matrix Method (TMM). At an optimum Silicon thickness, polarizer parameters like insertion loss and extinction ratio are calculated and tabulated. This paper provides rigorous analysis for silicon clad waveguide polarizer parameters for TE as well as TM polarization using same structure. A TM pass polarizer with extinction ratio of about 690 dB and insertion loss of about 2.8 dB and a TE pass polarizer with extinction ratio of about 289 dB and insertion loss of about 1.5 dB is proposed for a length of 1mm.*
Keywords*: Silicon-clad waveguide, TE/TM pass polarizer, extinction ratio, Transfer matrix method.*

I. Introduction

Multilayer waveguides are used in the implementation of variety of optical devices including modulators, waveguide polarizers, semiconductor lasers, Bragg reflectors, directional couplers and sensors[1-7]. Polarizer is an important component in optical communication and sensor systems[2,3]. For selecting a particular polarization, different polarizers utilize different techniques like birefringence, resonant mode coupling and different TE/TM level of absorption in multilayer waveguides [5]. To implement these techniques various kind of material are used as specific layers (cladding, buffer) in the waveguide structures [6]. The polarization property which is used in this paper is to selectively attenuate the TE or TM modes of the optical waveguide, resulting in a TM-pass or TE-pass polarizer [7]. Indium-Tin-oxide (ITO), a wide band gap semiconductor which comes under the group of transparent conductive oxides, has been used successfully as an absorbing layer to select a specific polarization [8-9]. Planar waveguides with semiconductor cladding exhibit various interesting characteristics due to presence of regions of selected high and low attenuation for different polarization modes (TE/TM) of the propagating light at different spectra [10-12]. Unlike metal cladding on dielectric guides which mainly attenuate the TM mode, a semiconductor cladding allows the selective attenuation of either TE or TM polarization [13-14]. The design of TE/TM pass polarizer with metal clad high index buffer layer has also been proposed in a previously published article[15]. But to design polarizers with such a technique, expensive metals like Au and Ag are needed for cladding layers. High index buffer layers are also the additional requirement in designing good extinction ratio polarizers with metal clad waveguides. On the other hand, silicon comes in the category of most abundant material on the earth and is not very expensive. Also in case of silicon clad waveguides efficient polarizers may be designed without buffer layers. In earlier times, silicon clad optical waveguide structures have been studied [16] for polarization effects, but a complete theoretical analysis for polarizer parameters like high extinction ratio and low insertion loss is yet to be done for both polarizations. Polarization and frequency selective effects in Silicon-Clad waveguide have been observed many times with complex methods like FEM [17-19].In this work instead of complex methods, we used Transfer Matrix Method (Appendix-A) which is very simple and reliable method [20-23]. It has been observed that by changing the thickness of semiconductor cladding layer, the TE or TM modes in dielectric guiding layer may be selectively attenuated. This polarization effect is due to the coupling between lossy modes of the dielectric waveguide and modes supported by silicon cladding layer.

We propose that by selecting a specific thickness of silicon layer (cladding) a particular polarization mode can be passed with a negligible loss and at the same thickness other polarization mode can be rejected with very high attenuation value. In other words at some critical value of silicon thickness, an integrated polarizer with high extinction ratio can be designed for both polarizations. All the necessary parameters for TE and TM polarizations have been calculated and tabulated. Along with attenuation and dispersion curves, field profiles are also generated to support the results. The complex eigenvalue equation describing the structure is exactly solved numerically by Muller's method [22].

II. Mode Solutions For Three/Four Layer Silicon Clad Waveguide

Fig.1 shows the three layer silicon waveguide structure and coordinates. The substrate and air cover are considered to be lossless and are presented by real refractive index values.

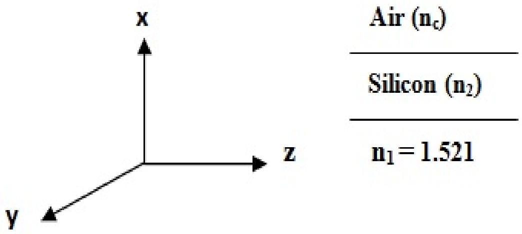


Fig. 1 Three layer lossy silicon waveguide structure (n_1= 1.521, n_2 = 4.1 - 0.211i, n_c = 1.0)

Silicon as a lossy guiding layer is characterized by a complex value of refractive index at the wavelength of 0.6328µm. The cover (air) and substrate layer are assumed to be semi-infinite. The values of the structural parameters used in the analysis of three/four layer silicon clad waveguide are given in Table 1. The modes of the waveguide are characterized by a complex propagation constant given as $jk_z = \alpha + j\beta$. Where α is the absorption loss in the waveguide structure and β / k_o is the mode effective refractive index.

Table 1. Parameters used to analyse the proposed structures

λ= 0.6328 µm		
Layer	**Index**	**Thickness**
Air	1.0	Semi-infinite
Silicon	4.1 - 0.211 i	d_2
Guiding layer	1.521	d_1=1.5 µm
Substrate	1.512	Semi-infinite

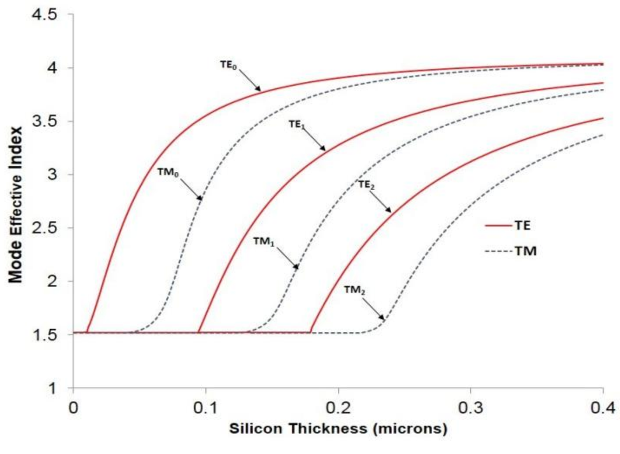


Fig. 2 Lossy modes supported by silicon waveguide

Transfer Matrix Method is used to find eigen modes in the planar waveguide structure [24]. Transfer matrix of each layer is calculated, and the dispersion equation for the waveguide structure has been obtained. The resulting dispersion equation for both TE and TM modes is solved by numerical iteration method. Fig.2 shows the modes supported by silicon waveguide for both polarizations. These modes are the guided modes propagating in silicon layer. For the proposed four layer structure, these modes will behave as lossy modes supported by silicon thickness. Fig.3 shows the proposed structure of four layer silicon clad waveguide. The waveguide considered is a lossless single mode potassium ion exchange glass waveguide in microscopic glass slider with guide thickness (d_1) of 1.5µm, which is sufficient to support fundamental TE_o and TM_o modes. The glass waveguide supports only the fundamental modes; however as the thickness of the silicon layer is increased the number of modes supported by composite structure increases but having very high losses. For the proposed structure the role of silicon thickness is as a cladding layer. Here also the same TMM is employed to find the mode solutions.

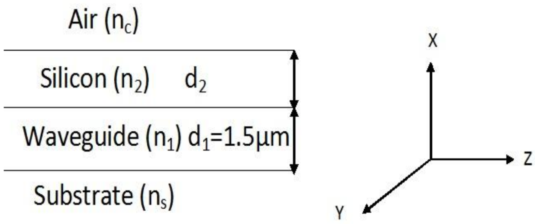
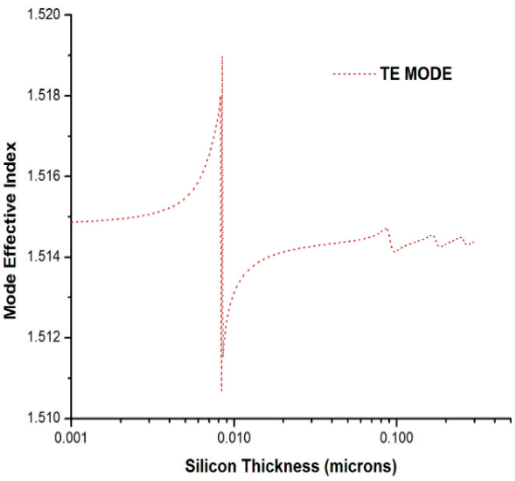


Fig. 3 Proposed silicon clad waveguide structure for TE/TM pass polarizer (n_c = 1.0, n_1= 1.521, n_2 = 4.1 - 0.211i, n_s= 1.512, d_1= 1.5 µm)

III. Results And Discussion

TM Pass Polarizer:

Let us now consider the proposed structure (as shown in Fig.3) with the selected values of the waveguide parameters for the feasibility of designing an integrated polarizer. Fig.4 shows the variation of mode effective index with the silicon layer thickness. For three layer silicon waveguide structure, mode index find its maximum value around the value of real part of silicon refractive index. In case of four layer composite structure, mode index is restricted to the value around the refractive index of guiding layer which shows that it is a coupled guided mode. From Fig.4, it is also clear that initially the mode effective index increases with the thickness of the silicon layer and become maximum at the critical thickness.



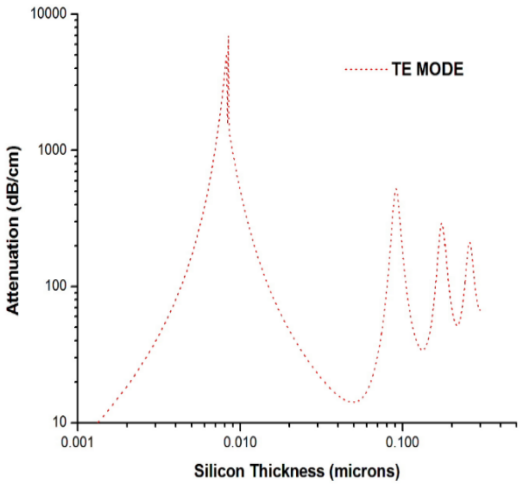


Fig. 4 Variation in mode effective index with Si Thickness **Fig. 5** Attenuation peaks due to periodic coupling

At this thickness, complete phase matching between the guided mode and lossy mode takes place and almost all the energy of the guided TE mode is shifted into the cladding layer where it is absorbed. On increasing silicon thickness further, the mode effective index decrease and then again increase, where the guided mode now couples to the next higher mode supported by the silicon. This phase match is present at each of the successively higher order TE (lossy) mode cut-off thicknesses and corresponds to the respective attenuation peak for the composite structure. Fig.5 shows that for the silicon thickness of 0.0084µm, there is a sharp peak of attenuation for TE mode. The loss at this thickness is about 6930 dB/cm and the corresponding loss for TM polarization is extremely low as shown in Fig.7. This may lead to design a TM pass polarizer with high extinction ratio. Waveguide modes can be best analysed using field plots. Fig.8 shows the field plot for both polarizations (TE/TM) for the silicon thickness of 0.0084 µm plotted as a function of the waveguide cross section. It is clear that the field confinement for TE mode in silicon layer is much better than TM mode. There is no resonant coupling for TM mode in silicon layer and most of its energy is confined to the waveguide. Therefore, at this Silicon thickness, a TM pass polarizer with extinction ratio of 690 dB and insertion loss of 2.8 dB can be designed for the polarizer length of 1mm. One another peak of attenuation can be seen in fig.5 at around 0.091µm thickness of silicon, but in this case attenuation is not equally high.

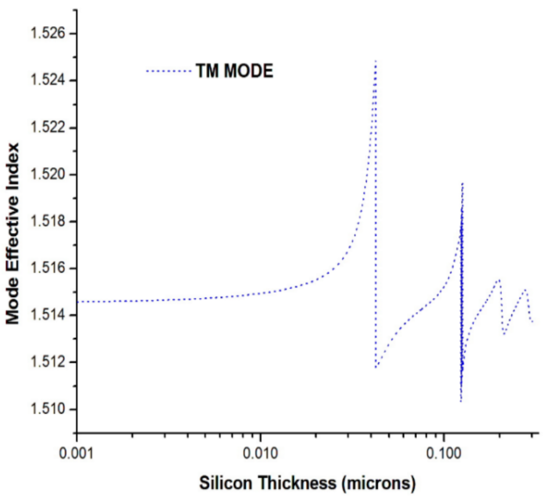


Fig. 6 Variation in mode effective index with Si Thickness

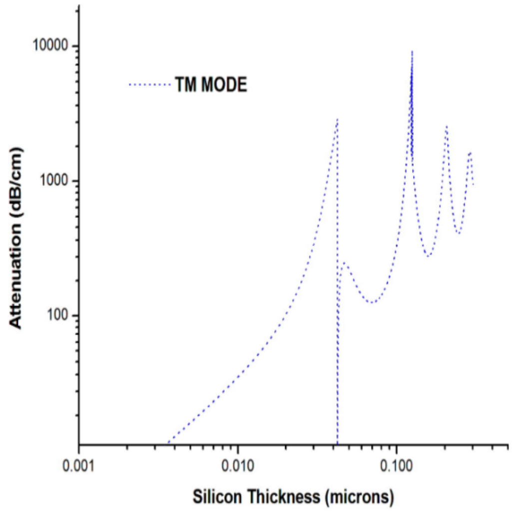


Fig. 7 Attenuation peaks due to periodic coupling

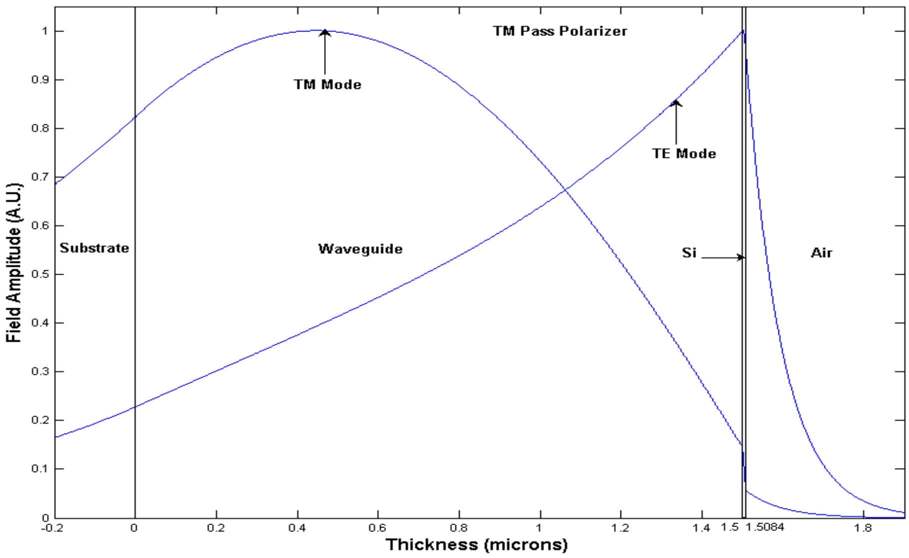


Fig. 8 Electric field profile for TM pass polarizer

The calculated parameters for TM pass polarizer are also shown in Table 2. The results for silicon clad waveguide polarizer are better in comparison to wide band gap ITO clad waveguide polarizer [9].

Table 2. Calculated values of effective index as a function of silicon thickness to design a TM pass polarizer

Silicon Thickness (μm)	Effective Index (TE MODE)	Effective Index(TM MODE)
0.0081	1.517747802640989 + 0.005099694234410986 i	1.514863301573929 + 0.00003167060889960691 i
0.0082	1.518011190145012 + 0.005966548653843502 i	1.514867534665641 + 0.00003212068170406507 i
0.0083	1.510695098479358 + 0.001808509342681004 i	1.514871780909387 + 0.00003257303473184972 i
0.0084	**1.518976244034581 + 0.008022505119926038 i**	**1.514876040471439 + 0.00003302770561573827 i**
0.0085	1.511517170087975 + 0.001605354612293939 i	1.514880313519692 + 0.00003348473245884144 i
0.0086	1.511797361399493 + 0.001483191140167223 i	1.514884600223686 + 0.00003394415384373037 i
0.0087	1.512018014224988 + 0.001367826133559224 i	1.514888900754638 + 0.00003440600884173518 i
Extinction ratio = 690 dB	**Insertion loss = 2.8 dB**	

TE Pass Polarizer:

Using the same principle of selective attenuation in the proposed structure a TE pass polarizer can also be designed. Variation of attenuation and mode effective index as a function of silicon thickness is shown for TM polarization in Fig.6 and Fig.7 respectively.

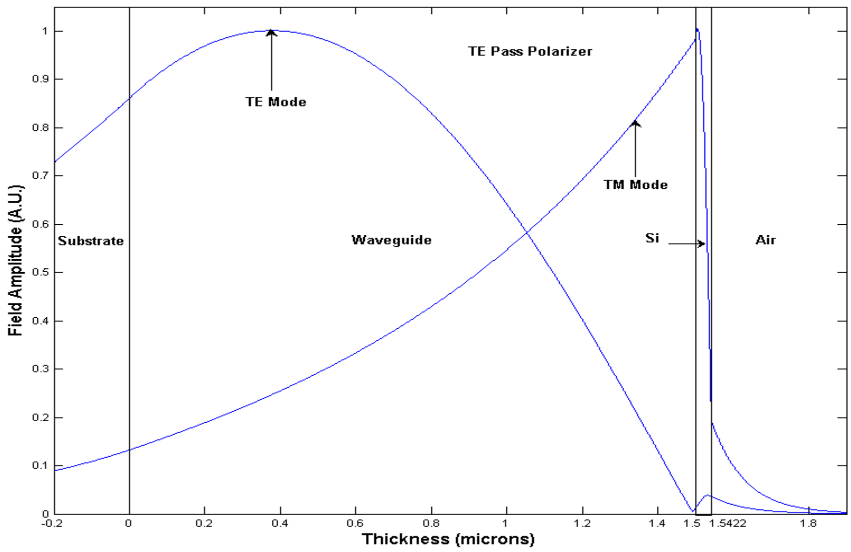


Fig.9 Electric field profile for TE pass polarizer

A similar nature is observed for TM polarization as that for TE. The first strong peak appears at silicon thickness of 0.0422 µm. The loss for TM mode at this thickness is about 2900 dB/cm. The corresponding loss for TE mode is very low as shown in Fig.5. These results clearly indicate that a TE pass polarizer of the length of 1mm can be designed with the extinction ratio of 289 dB and insertion loss of 1.5 dB. The possibility of designing TE pass polarizer is also supported by the field profile, plotted for both polarizations as shown in Fig.9. It is clear that most of the energy of TM mode is confined in the silicon cladding and the corresponding energy of the TE mode is mostly confined within the waveguide region. For this case, calculated parameters are shown in table 3.

Table 3. Calculated values of effective index as a function of silicon thickness to design a TE pass polarizer

Silicon Thickness (µm)	**Effective Index(TE MODE)**	**Effective Index(TM MODE)**
0.0419	1.514348201645242 + 0.000017689864815282 58 i	1.524379353471867 + 0.003191996222228512 i
0.0420	1.514348728297497 + 0.00001765618528622725 i	1.524531146630507 + 0.003246538602552282 i
0.0421	1.514349253822935 + 0.00001762298824014982 i	1.524685411699306 + 0.003301759564646406 i
0.0422	**1.514349778239709 + 0.00001759027165308593 i**	**1.524842174121772 + 0.003357660756981020 i**
0.0423	1.514350301565835 + 0.00001755803355756443 i	1.511760392051351 + 0.000008192444697288 74i
0.0424	1.514350823819193 + 0.00001752627204210397 i	1.511771637844673 + 0.00002739098938874633 i
0.0425	1.514351345017523 + 0.00001749498525072463 i	1.511783082408184 + 0.00004545352197503982 i
Extinction ratio = 289 dB	**Insertion loss = 1.5 dB**	

Although in this paper, a complete theoretical analysis of the silicon clad waveguide structure has been performed. But polarizers for both polarizations as suggested can be experimentally realized easily. The theoretically assumed ion exchanged waveguide parameters like depth and index can be experimentally realized with precise control [25, 26]. Silicon film can also be easily deposited on ion exchange glass waveguides and also these Silicon-on-insulator (SOI) devices have excellent compatibility with Complementary metal-oxide-semiconductor (CMOS) technology [27]. Our results show that silicon layer starts supporting high TE attenuation peaks from a thickness of 0.0084µm. A similar observation can be seen in an experimental study of slightly different waveguide structure at the wavelength of 633 nm [14].

IV. Conclusion

We have analysed in detail the silicon clad optical waveguide structure for high extinction ratio TE/TM pass polarizers at the wavelength of λ = 0.6328 µm. It is observed that due to periodic coupling between lossy modes supported by silicon and guided modes of guiding layer, these structures exhibit a damped oscillatory behaviour in their attenuation characteristics. If the structural parameters of the Si clad waveguide are selected properly, sharp resonance peaks of the TE/TM modes can be obtained. Unlike metal cladding on dielectric guide which mainly attenuate TM modes, semiconductor (silicon) cladding allows the selective attenuation of either TE or TM modes. We have demonstrated that both TE and TM pass polarizer with high extinction ratio and low insertion loss can be designed. Results of this analysis may lead to design very compact and highly efficient TE/TM pass integrated polarizers, which are very important in the field of optical communication. Field profiles also support the feasibility of designing the proposed polarizers with selected values of the waveguide parameters. The losses of the passing modes may be further reduced by inserting buffer layer between cladding and guiding layers.

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