Fiber-Optic Polarizer Using Resonant Tunneling through a Multilayer Overlay

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We demonstrate an in-line fiber-optic polarizer using resonant tunneling through a leaky multilayer overlay for the first time. Polarization extinction ratio (PER) = 27 dB with an insertion loss (IL) = 3 dB has been demonstrated experimentally with scope of further improvement. A simple planar waveguide model is developed to analyze the device whose predictions match very well with the experimental results. It is further shown that by properly selecting the device parameters one can achieve PER = 68 dB with IL = 0.2 dB for A = 0.6328 μm and PER = 80 dB with IL = 12 dB for A = 13 μm.

INTRODUCTION

Many fiber-optic systems such as coherent communication systems, gyroscopes, and fiber interferometers require polarization control. Integrated-optic polarizers have high insertion loss (IL) due to the mode mismatch between the fiber and the integrated optic waveguide. Thus in-line fiber-optic polarizers are preferred over the others, and various in-line fiber polarizers have been reported in the literature [1-6]. Among these, polarizers using thin metal films have received maximum attention. Such polarizers, however, can act only as TE pass polarizer as metal coated waveguides attenuate only TM waves [5]. In Ref. [6], Creaney et al. have reported a polarizer which can act both as TE/TM pass polariser, in which they have used the phenomenon of a normal directional coupler by matching the fiber mode effective index with that of one of the polarization modes of a multimoded dielectric planar waveguide. But as they have mentioned in their paper, this device...
is suitable only to obtain moderate polarization extinction ratio (PER). Thyagarajan et al. [7] have proposed an integrated optic polarizer based on the resonant tunnelling effect which can also be designed to act either as a TE or a TM pass polarizer and have shown theoretically that with proper choice of materials one can obtain PER \( \sim 80 \) dB with an insertion loss for throughput polarisation as low as 0.5 dB. Using the same configuration Asakawa et al. [8] have proposed a wavelength filter also. This paper reports the first experimental implementation of this principle as a fiber optic polarizer.

PROPOSED DEVICE AND ITS WORKING PRINCIPLE

A schematic diagram of the proposed device is shown in Fig. 1. A single mode fiber, polished very near to the core-cladding interface, has top layers of high index (Si), low index (SiO\(_2\)) of appropriate thickness and a thick capping layer of high index ( \( \geq \) fiber core index). The thin Si layer acts as a leaky waveguide which has a large difference between the effective indices of its TE and TM modes due to its high core index as compared to the surroundings (SiO\(_2\)). By appropriate choice of the thickness of this layer, the effective index of the fiber mode can be matched to one of the TE or TM (preferably) modes of the waveguide. Depending on which mode (TM or TE) is phase matched, the TM (TE) component of the unpolarized light launched in the fiber couples strongly to the phase matched TM (TE) mode of the planar waveguide and experiences high leakage loss (much like as in quantum mechanical tunneling). The other polarization, i.e., TE (TM) component experiences very little loss. The device thus acts as a TE (TM) pass polarizer.

EXPERIMENT

In order to demonstrate the proposed device a single-mode (at \( \lambda = 0.6328 \) \( \mu \)m) fiber is held in a silica block with a groove of radius of curvature \( \sim 25 \) cm and then polished very close to the core. The distance of the core from the polished surface (\( \sim 0.2 \) \( \mu \)m) and \( n_{\text{eff}} \) of the fiber (\( \sim 1.460 \)) were estimated by measuring the insertion loss with overlay index [9] using different index matching liquids (from Cargile Labs., USA). A separate Si substrate covered with layers of SiO\(_2\) (2.6 \( \mu \)m)

![Diagram](attachment:diagram.png)

FIG. 1. (a) Schematic diagram of the proposed device; (b) refractive index profile in the central cross-section.
and Si (0.1 μm) is used as a multilayer overlay on top of the polished half-block with an index matching liquid in between for a better optical contact. Unpolarized light is launched into the fiber with the help of a microscope objective (MO). The output power, measured through a rotating linear analyzer, varies periodically and the polarization state corresponding to the maximum and minimum output powers are found to be TE and TM polarizations, respectively. Pressure is applied on the overlay to optimize the oil thickness to maximize the coupling between the fiber and planar waveguide mode. The device characteristics are also found to be sensitive to the oil index. This is because the oil index changes the effective indices of the modes of the overlay, changing the coupling between the fiber modes and the overlay. Figure 2 shows the variation of the measured PER and insertion loss with the oil index. The best extinction ratio was measured to be ~27 dB with an insertion loss ~3 dB, obtained by selecting $n_{oil} = 1.464$. However, polarizers with very high PER and low insertion loss can be realized by optimizing the various device parameters as discussed later in this paper.

THEORETICAL CALCULATIONS

Assuming that the thin layer of Si is surrounded on both sides by SiO$_2$ ($n = 1.4573$); the resulting symmetric planar waveguide supports two TE and two TM modes, with effective indices as $TE_0 = 3.33544$, $TE_j = 1.60058$, $TM_0 = 2.67627$, $TM_j = 1.45948$ at $A = 0.6328$ μm where the refractive index of Si is taken to be $(3.881 - i 0.019)$ [10]. The above calculations show that none of the modes supported by the Si layer is exactly phase matched with the fiber mode. The mode nearest to phase matching is $TM_j$ with an effective index slightly lower than

![Graph showing variation of PER and insertion loss with oil index](image)

**FIG. 2.** Experimental results showing the variation of PER and insertion loss with the oil index.
that of the fiber mode. The phase matching condition can, however, be met between this (TMj) mode and the fiber mode by introducing a liquid of index higher than that of fiber cladding between the fiber and the overlay, increasing the $n_{\text{eff}}$ of the TMj mode, which in turn should increase the PER. Our experimental results are consistent with this theoretical prediction as the maximum PER is obtained for $n_{\text{oil}} = 1.464$, which is higher than that of the fiber cladding (1.4573).

**Planar Waveguide Model**

In order to estimate the PER and the insertion loss of the device theoretically, we replace the fiber by a planar waveguide having the same core-cladding indices of width $(d)$ equal to the fiber-core radius $(r)$; the distance of the waveguide from the overlay is thus taken to be $u(z) + r/2$, where $u(z)$ is the remaining cladding thickness of the fiber. Such an approach was used by Thyagarajan et al. [11] to analyze a metal clad fiber optic polarizer successfully. The $z$-variation of the half-block is taken into account by breaking the curved fiber into a large number of straight sections ($\geq 700$). Further, while calculating the TE/TM mode losses, we consider only that mode of the composite structure whose overlap with the fiber (now the planar waveguide) mode is maximum. This approach is justified as initially the fiber core is well separated from the overlay and the light launched in the fiber couples mainly to one of modes of the composite structure only. To make this point more clear we have plotted in Fig. 3 the modal field of the fiber as well as the modal fields of the TM modes of the composite structure at the input of the coupling region at $A = 0.6328 \text{ pm}$. The overlap integral of the fiber mode with the TMj mode of the composite structure is found to be $\sim 99.9\%$, which clearly shows that power from the fiber TM mode is initially launched mostly in this mode only. Further, in a polished half-block due to large radius of curvature the distance between the fiber and the overlay structure decreases gradually and hence the power is expected to remain mainly in the considered mode only. The resulting planar waveguide system is then analyzed by using the transfer matrix method [12].

![](image)

**FIG. 3.** Normalized modal fields of the fiber and the TM$_0$ and TMj modes of the composite structure at the input of the coupling region. The fiber and the TMj modes are indistinguishable in the figure. The dashed line around $X = 8.1 \text{ nm}$ shows the position of thin Si layer.
and the resulting complex eigenvalue equation is solved by using the steepest descent method. This gives us complex eigenvalues at each value of $z$, the imaginary part of which determines the loss of the particular mode. The total loss of TE/TM mode is then evaluated by integrating over $z$. Using the above method we first calculated TE/TM mode losses corresponding to the device studied experimentally. For that we calculated TE/TM mode losses as a function of the oil thickness since in the experiment oil thickness was varied to get maximum PER. The value of $n_{oil}$ is taken to be 1.464, which corresponds to the maximum PER observed experimentally. Figure 4 shows the variation of the TE and TM mode losses as a function of oil thickness. It is clear from the figure that the PER ($= 4.343 \times (TM_{loss} - TE_{loss})$) is a sensitive function of oil thickness, and the maximum PER obtained is $\approx 26$ dB (for $d_{oil} \approx 2.5$ μm), which agrees very well with the experimental results. At this value of oil thickness the insertion loss ($= 4.343 \times TE_{loss}$) is <1 dB, which is lower than the observed value (3 dB) and can partially be attributed to the fact that in the present theoretical modeling, coupling to the other TE modes supported by the composite structure and the coupling loss between the fiber and the composite structure mode is neglected. Encouraged with the agreement between the theoretical and the experimental results we use this planar waveguide model to find the optimum performance of such a device.

**Design Considerations**

The performance of the proposed device can be improved by observing the following points:

(i) the parameters of the overlay structure should be chosen such that it is single moded (supporting TE₀ and TM₀ modes only) and the fiber mode is phase

![Image](image.png)

*FIG. 4.* Theoretical results showing the variation of TE and TM mode losses with the oil thickness for $n_{oil} = 1.464$. 
matched with the TM$_0$ mode. Since the difference between $n_{\text{eff}}$ of the TE$_0$ and TM$_0$ modes is much larger than that of TE$_j$ and TM$_j$ modes, coupling between the fiber mode to the TE mode of the overlay will be much smaller leading to the lower insertion loss and higher PER. In view of the above the device fabrication tolerances at $A = 13$ $\mu$m and $A = 15$ $\mu$m are expected to be better as the width of Si layer required for SM operation of the overlay will be larger than that at 0.633 $\mu$m.

(ii) The insertion loss can be further reduced by selecting the topmost layer refractive index lying in between the effective indices of the TE$_0$ and TM$_0$ modes. In that case only TM$_0$ mode will be leaky, leading to better PER and lower insertion loss.

(iii) Finally, it would be better if the overlay waveguide were deposited directly on the block itself, making the device insensitive to temperature variations (as $n_{\text{oil}}$ changes with temperature).

Taking into account the above design criteria, we have obtained the device parameters to give maximum PER at $A = 0.6328$ $\mu$m and $A = 13$ $\mu$m and the corresponding IL by taking the index of top layer equal to the fiber core index (1.46136) and also without considering the oil layer in between the fiber and the overlay.

For $A = 0.6328$ $\mu$m first the width of Si layer ($d_{si}$) was selected to be $= 0.0088$ $\mu$m, as at this thickness Si layer supports only one TE and one TM mode and the $n_{\text{eff}}$ of its TM mode matches with the $n_{\text{eff}}$ of the fiber (let us call this thickness $d^{f'}$). Then the PER and insertion loss were calculated using various values of $w(0)$ and the second cladding thickness ($d_2$). The optimum values of $d_2$ to give maximum PER at each value of $w(0)$ and the corresponding PER and IL are shown in Table 1. The results show that by properly selecting $w(0)$ and $d_2$ one can obtain PER as high as $\sim 68$ dB with insertion loss $\sim 0.2$ dB. Table 1 also shows that both PER and insertion loss increase with decrease in $w(0)$. This is understandable since as $w(0)$ decreases there would be a better coupling between the fiber and the multilayer overlay, thus leading to an increase in the loss for both type of modes. Similar calculations were carried out for $A = 13$ $\mu$m. Here $d^{f'}$ comes out to be $\sim 0.012$ $\mu$m (which as predicted is more than $d_{l^1}\gamma^l$ required at $A = 0.6328$ $\mu$m). A

<table>
<thead>
<tr>
<th>$M(0)$ ($(\mu$m)</th>
<th>$d_2$ ($\mu$m)</th>
<th>PER (dB)</th>
<th>IL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.74</td>
<td>68.191</td>
<td>0.216</td>
</tr>
<tr>
<td>0.1</td>
<td>0.82</td>
<td>63.894</td>
<td>0.175</td>
</tr>
<tr>
<td>0.2</td>
<td>0.87</td>
<td>59.803</td>
<td>0.140</td>
</tr>
<tr>
<td>0.3</td>
<td>0.91</td>
<td>55.330</td>
<td>0.113</td>
</tr>
<tr>
<td>0.4</td>
<td>0.95</td>
<td>51.088</td>
<td>0.091</td>
</tr>
<tr>
<td>0.5</td>
<td>0.99</td>
<td>47.093</td>
<td>0.074</td>
</tr>
</tbody>
</table>
TABLE 2
PER and IL for Various Values of $d_{Si}$ around $\lambda = 1.3 \mu m$

<table>
<thead>
<tr>
<th>$d_{Si}$ (nm)</th>
<th>PER (dB)</th>
<th>IL (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0120 (optimum value)</td>
<td>80.541</td>
<td>1.192</td>
</tr>
<tr>
<td>0.0126 (opt. + 10%)</td>
<td>76.498</td>
<td>1.067</td>
</tr>
<tr>
<td>0.0114 (opt.- 10%)</td>
<td>74.422</td>
<td>1.339</td>
</tr>
</tbody>
</table>

The proper choice of $w(0) (= 1.2 \mu m)$ and $d_{2} (= 1.1 \mu m)$ leads to high PER $\sim$ 80 dB with IL = 12 dB (Table 2).

We would like to mention that thickness of the Si layer involved is very small and hence the fabrication tolerance of the device with respect to this thickness is extremely important to know. We carried out calculations to see the effect of $d_{Si}$ on the PER and IL by making a $\pm 10\%$ variation in $d_{f}$ (Table 2). The calculations show that although there is a decrease in the PER, the change is only $\leq 7.5\%$. One more item of note is that as $d_{Si}$ decreases the insertion loss increases. This is understandable, as when $d_{Si}$ decreases the effective index of the TE mode supported by the Si layer decreases and comes nearer to the fiber mode effective index, which in turn leads to an increase in the coupling with the fiber TE mode and hence its loss.

Another important parameter is the bandwidth of such a polarizer. We have also studied how the PER and IL of the designed device change as the wavelength is changed around 1.3 $\mu m$. Our calculations show that by changing the wavelength by $\pm 10$ nm the PER and the IL change by $\leq 0.4$ and $\leq 1.8\%$, respectively, around $\lambda = 1.3 \mu m$. This shows that the device is not very sensitive to the fluctuations in the wavelength around the operating wavelength.

CONCLUSION

In conclusion, we have proposed and demonstrated an in-line fiber-optic polarizer using differential polarization-mode loss due to resonant coupling to a leaky multilayer overlay for the first time. A simple planar waveguide model is developed to analyze such a device whose predictions match very well with the experimental results. Further calculations show that with proper choice of device parameters one can achieve very high PER with low insertion loss.

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