Resonant Tunneling Three-Waveguide Polarization Splitter

K. Thyagarajan and Saeed Pilevar

Abstract—We propose the design of a novel and highly efficient all-dielectric, three-waveguide polarization splitter based on the phenomenon of resonant tunneling. By considering a glass waveguide structure with an intermediate high-index guiding layer (such as silicon), we show that one can obtain extinction ratios better than -30 dB in both the outer waveguides at a particular thickness of the high-index layer. We have also estimated the tolerance required with respect to the separation between the middle and outside guides and the thickness of the high-index layer of such a device. The proposed design should be of interest in the realization of in-line fiber-optic polarization splitters and in integrated optics.

I. INTRODUCTION

POLARIZERS and polarization splitters are important components of coherent optical communication systems and fiber-optic sensors. A polarization splitter differs from a polarizer in that no energy is intentionally lost; both polarizations emerge from the device in separate channels. Various polarization splitters based on different principles have been demonstrated by different authors. These include a metal clad directional coupler [1], [2], a y-branched waveguide [3] and a reversed A/3 directional coupler [4], [5]. Recently, a four-port integrated optic polarization splitter based on a Mach-Zehnder interferometer [6] was demonstrated using silicon optical bench technology.

In this paper we propose the design of a novel, all-dielectric, three-waveguide polarization splitter based on the phenomenon of resonant tunneling. The resonant tunneling principle was recently exploited in the design of both TE pass and TM pass polarizers [7]. Here we consider a structure with a large refractive-index difference between the guiding region and the surrounding. This large difference can be made use of in the construction of polarization selective devices based on resonant tunneling principle [7]. The proposed configuration, the thin high-index layer (WG2) is so chosen that its TM mode is almost resonant with the TM mode of the outer waveguides. Due to the large refractive index of the guiding region of WG2, its TE mode will be completely nonresonant with the TE modes of the outside waveguides (see Fig. 1). The middle high-index layer is so chosen that its TM mode is almost resonant with the TM modes of the two waveguides, while its TE mode is not resonant with those of the outer waveguides. We shall show in Section II that such a structure can act as an efficient polarization splitter.

The operation of the device is based on the fact that the difference in propagation constants of TE and TM polarizations of a waveguide can be increased by having a large refractive-index difference between the guiding region and the surrounding. This large difference can be made use of in the construction of polarization selective devices based on resonant tunneling principle [7]. In the proposed configuration, the thin high-index medium (WG2) is so chosen that its TM mode is almost resonant with the TM mode of the outer identical guides. Due to the large refractive index of the guiding region of WG2, its TE mode will be completely nonresonant with the TE modes of the outside guides (see Fig. 2). Thus unpolarized light launched into WG1 (say) will resonantly couple to TM polarization in WG3 and will exit from WG3. On the other hand, TE polarization cannot couple resonantly and exits mainly from WG1.

The operation of the polarization splitter can also be investigated in terms of the supermodes of the three-wave-
guide directional coupler. If the individual isolated guides of the coupler are single moded, then the coupled structure would support three modes, namely two symmetric and one antisymmetric. Let \( p_a, o_b, \) and \( p_e \) represent the propagation constants of the two symmetric and the antisymmetric mode respectively for each of the polarization states. According to Donnelly et al. [8], the power transfer efficiency from one outside guide to another can be maximized, if propagation constants of the three propagating modes satisfy the condition:

\[
\delta_{\lambda} - \delta_{C} = P_{C} - P_B \tag{1}
\]

i.e.,

\[
W_0 - P_A \sim P_B = 0. \tag{2}
\]

For power launched into an outside guide (say WG1), the power emerging from waveguides 1 and 3 at any length of the coupler \( L \) can be found using the procedure outlined in [9]. Neglecting reflections at the input and output and assuming that power coupled into radiation modes at the input and output are lost we obtain for the power outputs \( P_{o1} \) and \( P_{o3} \) from waveguides 1 and 3, respectively, at the output of the coupler of length \( L \):

\[
P_{o1} = M_1 + M_2 + M_3 + 2M_1M_B \cos(p_A - p_B)L + 2M_A M_C \cos(p_A - p_C)L + 2M_B M_C \cos(p_B - p_C)L \tag{3}
\]

and

\[
P_{o3} = N_1 + N_2 + N_3 + 2N_1N_B \cos(p_A - p_B)L + 2N_A N_C \cos(p_A - p_C)L + 2N_B N_C \cos(p_B - p_C)L \tag{4}
\]

where

\[
M_j = \int_{-\infty}^{\infty} E_j(x)E_j(x)dx \tag{5}
\]

and

\[
N_j = \int_{-\infty}^{\infty} E_j(x)E_3(x)dx \tag{6}
\]

with \( E_j(x) \), \( j = A, B, C \) are the normalized transverse field profiles (electric field for TE modes and magnetic field for TM modes) of the \( j \)th mode of the three guide coupler, and \( E_3(x) \) and \( E_3(x) \) represent the normalized field profiles of the mode of the input guide (WG1) and the mode of the output guide (WG3), respectively.

If we choose the parameters of the coupler to satisfy the condition \( 2p_0 - p_A - p_B = 0 \), i.e., if the propagation constants of the supermodes of the coupler are equally spaced and the length of the coupler \( L \) is \( n/A \) (\( A/3 \) is the propagation constant difference of any two adjacent modes), the phase difference between the adjacent modes will be \( n \). Since the propagation constants of the symmetric and antisymmetric modes are placed alternately, the effective phase difference between the two symmetric modes is zero, and that between the symmetric and antisymmetric modes is \( n \). Thus, if the fields of symmetric modes at the output end of the coupler remain unchanged the fields of the antisymmetric mode will reverse in phase. This causes the superposition of all the modes at the output end to be the reflection of the field at the input end about the symmetric plane. Thus, the peak of the superposed field reproduces on the opposite guide at the output end, and a complete power transfer between the fields at the input and the output end is obtained.

In the proposed configuration, the presence of the middle high-index layer causes a strong interaction for the TM modes between the outer guides through resonant tunneling via the intermediate high-index layer, while for the TE mode the interaction is much weaker. Thus, it should be possible to choose the parameters such that:

\[
(P_A - P_C)/TM = (P_C - P_B)/TM \tag{7}
\]

and

\[
P_A - P_{chv} > (P_C - P_{chv}) \tag{8}
\]

If we now choose a coupler of length \( L = n/(P_A - P_C)/TM \), the TM polarization launched into WG1 will couple to TM polarization in WG3 and will exit from WG3, while the TE polarized light launched in WG1 would mainly exit from WG1.

The crosstalk in a three-guide coupler as shown in [10], is due to uneven spacing of propagation constants of three eigenmodes in the coupling region. The extinction ratios ER1 and ER3 are defined as

\[
ER1 = 10\log_{10} \left( \frac{\text{Exit power of TM polarization in WG1}}{\text{Exit power of TE polarization in WG1}} \right) \tag{9}
\]

\[
ER3 = 10\log_{10} \left( \frac{\text{Exit power of TM polarization in WG3}}{\text{Exit power of TM polarization in WG3}} \right) \tag{10}
\]

### III. RESULTS AND DISCUSSION

In order to show the applicability of the concept of the resonant tunneling polarization splitter, we consider a glass waveguide structure with an intermediate silicon layer having the following values of the various parameters [11], [7]:

\[
\begin{align*}
n_i &= 1.527, & n_s &= 1.5125, & n_3 &= 3.5 \\
a &= 2.0 \, \text{um}, & d &= 3.5 \, \text{um}, & A &= 1.3 \, \text{um}. & \tag{11}
\end{align*}
\]

The individual isolated guides of the above structure support only TE0 and TM0 modes. We have used the matrix method [12] to obtain the propagation constants of the TE and TM supermodes of the polarization splitter structure.
As mentioned earlier, the necessary condition for obtaining a high-power transfer efficiency between the outer guides is to make \(2\delta c - PA - PB\) equal to zero. Fig. 3 shows the plot of \(2\delta c - PA - PB\) for the TM polarization versus the thickness of WG2 \(2t\). As seen from the figure for the parameters given in (11) at \(2t = 0.0315 \mu m\), the propagation constants of the TM supermodes of the coupler become equally spaced. For the TE supermodes of the structure \((0_A - Pc) = 0.77694 \times 10^5 \mu m^{-1}\) and \((0_C - PB) = 8.1343 \times 10^5 \mu m^{-1}\) showing the high polarization dependence of the coupler. The extinction ratios ER1 and ER3 must be minimum at the point where \(2\delta c - PA - PB)TM = 0\). This is, indeed, shown in Fig. 4 which shows the variation of ER1 and ER3 versus the thickness of the WG2 \(2t\). All the values of the various parameters are as those given in (11) and length of the coupler is chosen to be \(L = 2TT/(0A - PB/TM)\). We see that at the same thickness of WG2 \(2t = 0.0315 \mu m\) where the condition \(2\delta c - PA - PB) = 0\) was satisfied for the TM modes, the value of extinction ratios in both outside guides are better than -30 dB.

The peak value of the extinction ratio ER1 and its width with respect to variation in the silicon layer thickness depends on the waveguide separation \(d\). As \(d\) decreases, the coupling between the modes of individual waveguides becomes stronger and one would expect the resonance to become broader with a lower peak value. In Fig. 5 we have shown the variation of the extinction ratio ER1 with the silicon layer thickness \(2t\) for three different \(d\) values, where the dashed, solid, and dashed-dotted curves correspond to \(d\) values of 2.5, 3.5, and 4.5 \(\mu m\), respectively. As expected, the resonance become broader and has a lower peak value as \(d\) decreases. Thus, the tolerance toward the silicon layer thickness can be increased by decreasing \(d\), although at the cost of slightly decreased extinction ratio.

We have also estimated the tolerance required for such a device with respect to the separation \(d\) between the middle waveguide and outside guides at \(2t = 0.0315 \mu m\), and the values of the other parameters are given in (11). Fig. 6 shows the plot of extinction ratios ER1 and ER3 versus the distance \(d\). It can be seen that the required tolerance in order to get extinction ratios greater than -20 dB in both outside guides is \(\pm 0.5 \mu m\).

IV. CONCLUSION

We have proposed a novel and highly efficient, all-dielectric, three-waveguide polarization splitter based on the phenomenon of resonant tunneling. Considering a glass waveguide structure we have shown that one can obtain extinction ratios better than -30 dB in both the outer waveguides at a particular thickness of the middle waveguide. We have also estimated the tolerance required with respect to the silicon layer thickness and the separation between the middle and outside guides of such a device. We have shown that the required tolerance in order to get extinction ratios better than -20 dB in both the outside waveguides is about \(\pm 0.5 \mu m\) in waveguide separation. The proposed configuration should find application...
in the construction of in-line fiber polarization splitters and in integrated optics.

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REFERENCES


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