Integrated mode-evolution-based polarization rotators

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For the first time to our knowledge, designs for mode-evolution-based integrated polarization rotators requiring only a pair of waveguide core layers are presented. Finite-difference time-domain and eigenmode expansion simulations demonstrate the near-ideal performance of the approach. In contrast with approaches based on mode coupling, no significant wavelength sensitivity is observed. © 2005 Optical Society of America

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High-index-contrast dielectric waveguides exhibit highly confined optical modes. The tight confinement allows for waveguides to be spaced closely together without inducing cross talk and the propagating field to be guided around sharp bends with minimal radiative loss. However, as the index contrast is increased, the differences between the lateral boundary conditions for TE and TM modes become more pronounced, causing critical device parameters, such as the propagation rate and coupling strength, to be polarization dependent. Although the geometry of the waveguides can be designed to compensate for one or the other of these effects for a particular device, it becomes difficult to compensate both simultaneously in a manner that applies to all devices on a high-index-contrast chip. To allow polarization-independent performance, a necessary feature for a standard single-mode-fiber-based communications link, the polarization sensitivity can be circumvented by the implementation of a polarization diversity scheme.[1,2] Such an approach requires the arbitrary polarization emanating from the fiber to be split into orthogonal components. Further rotation of one of the outputs allows a single polarization to be realized on chip and the two paths to be operated on in parallel with identical structures. An integrated approach allows for the devices to be batch fabricated with the path lengths of the arms matched through lithography.

Integrated optic approaches for splitting and rotating polarization states utilizing mode coupling have been proposed.[3–5] Yet, for complete power transfer, coupled modes must be phase matched and the degree of coupling precisely tuned to the structure length resulting in fabrication-intolerant and wavelength-sensitive devices. In contrast, devices based on mode evolution are fabricated tolerant and inherently broadband. Mode-evolution-based polarization splitters have been proposed,[6,7] and recently we presented an integrated approach for splitting and rotating polarization states through mode evolution.[8] In this Letter we describe an approach for mode-evolution-based polarization rotation, present example structures that require only two lithographic steps, and demonstrate their performance through both three-dimensional finite-difference time-domain[9] (FDTD) and eigenmode expansion[10] (EME) simulations.

A mode-evolution-based polarization rotator can be formed by twisting a waveguide. A twist rotates the axis and thus polarization states of the modes guided in the structure. However, a twist also induces coupling among the modes, extracting power from the initially excited mode. The evolution of the mode amplitudes $b_m(z)$ can be described by the coupled local mode equations:

$$\frac{\mathrm{d}b_m(z)}{\mathrm{d}z} + j\beta_m(z)b_m(z) = \sum_n \kappa_{mn}(z)b_n(z), \tag{1}$$

where $\beta_m(z)$is the local propagation constant of mode m and $\kappa_{mn}(z)$ is the local coupling coefficient between modes m and n given by

$$\kappa_{mn}(z) = \frac{\omega}{4\delta\beta(z)} \int \mathbf{e}_m^*(x,y,z) \cdot \mathbf{e}_n(x,y,z)\frac{\mathrm{d}}{\mathrm{d}z}\,\varepsilon(z)\mathrm{d}A. \tag{2}$$

Here $\delta\beta(z) = \beta_m(z) - \beta_n(z)$ and $\mathbf{e}_m(x, y, z)$ represents the power normalized local vector electric field of mode m.[11] In the limit of weak coupling the terms $\sum_{n\neq k}\kappa_{mn}b_n$, where mode k is the initially excited mode, can be dropped because they are necessarily small. The coupling to a mode m is then determined to be

$$b_m(z) = b_k(0)\exp\left[-j\int_0^z \beta_m(z')\mathrm{d}z'\right] \times \int_0^z \kappa_{mk}(z')\exp[-j\overline{\delta\beta}(z)z']\mathrm{d}z', \tag{3}$$

where $\overline{\delta\beta}(z) = (1/z)\int_0^z \delta\beta(z')\mathrm{d}z'$ is the average difference between the propagation constants. In evolving structures the coupling coefficient varies slowly and can be replaced by its average and taken out of the integral in Eq. (3). Power P_m accumulated in mode m is then

$$P_m(z) = 2|b_k(0)|^2 \left|\frac{\overline{\kappa}}{\overline{\delta\beta}}\right|^2 [1-\cos(\overline{\delta\beta}z)], \tag{4}$$

with the total power lost from the initially excited mode k given by $\sum_{m\neq k}P_m$. To ensure rotation of the polarization state, the power exchange must be suppressed. According to Eq. (4), the power lost to a given mode can be minimized by maximizing the ratio of $\overline{\delta\beta}$ to $\overline{\kappa}$ for each mode, in effect allowing modes a

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chance to dephase before substantial power exchange takes place. The number of modes with propagation constants similar to the excited mode (i.e., guided modes) should therefore be minimized, and for modes that cannot be cut off the difference in their rates of propagation should be maximized. Use of a large aspect ratio waveguide ensures greatly differing rates of propagation. Additionally, for an achievable $\overline{\delta\beta}$ the ratio of $\overline{\delta\beta}$ to $\overline{\kappa}$ can always be increased through a longer transition since the coupling coefficient in Eq. (2) is proportional to the rate of change of the dielectric.

A slow twist in a waveguide with a large aspect ratio will induce polarization rotation. However, standard microfabrication techniques dictate layer-by-layer construction. Although a twist can be more accurately approximated with a large number of layers, it is highly desirable to minimize the number of layers so as to simplify the fabrication process. Gauss's law for dielectrics ensures that the fundamental mode takes on a polarization largely aligned with the principal axis of the waveguide even when the waveguide is a crude structure formed from a pair of rectangular dielectric cross sections.

Thus polarization rotation can be induced with only a pair of waveguide core layers. An example structure is depicted in Fig. 1(a). Here the layers are asymmetrically and oppositely tapered. The principal axis of the structure and polarization state of the fundamental mode rotate in unison along the transition. In contrast with a pure twist, the mode set changes, yet a large difference in the rates of propagation of the guided modes is maintained. The performance of the approach is demonstrated through both three-dimensional FDTD and EME simulations. In the chosen example the core index is that of silicon nitride (2.2) and the cladding that of silica (1.445). The dimensions are $w_1 = 0.4\ \mu$m, $w_2 = 0.8\ \mu$m, and $h = 0.4\ \mu$m, and thus the input and output waveguide cross sections are rotated versions of one another. For the FDTD simulations the input and output TE and TM modes were calculated with a finite-difference mode solver. A Gaussian pulse TM input mode was launched into the structure. Discrete Fourier transforms were taken at both the input and the output. Subsequently, mode overlaps were taken for each polarization and each frequency contained in the discrete Fourier transforms. EME results were obtained by use of only the two guided modes. FDTD and EME results as a function of the device length are plotted in Fig. 1(b) for a wavelength of 1.55 μm. Both indicate that power lost from the fundamental (TE output) mode is transferred to the secondary (TM output) mode confirming the intuition that interaction among guided modes determines device performance. Further, as predicted, longer transitions yield better performance, yet device lengths of only a couple of hundred micrometers ensure nearly ideal performance. The wavelength dependence of a 200-μm-long structure as determined from a FDTD simulation is shown in Fig. 1(c). No significant wavelength sensitivity or loss is observed across the 1.45–1.75-μm band.

Although the device in Fig. 1(a) can be fabricated with electron-beam lithography, optical lithography systems are not capable of resolving the fine features of the structure. As an alternative, the width of the upper layer can be held constant or tapered slightly while it is moved away from the lower section and into the evanescent field of the guided modes [Fig. 2(a)]. Doing so presents a trade-off: The minimum feature size is increased, but the planarization must now smoothly extend across material boundaries.

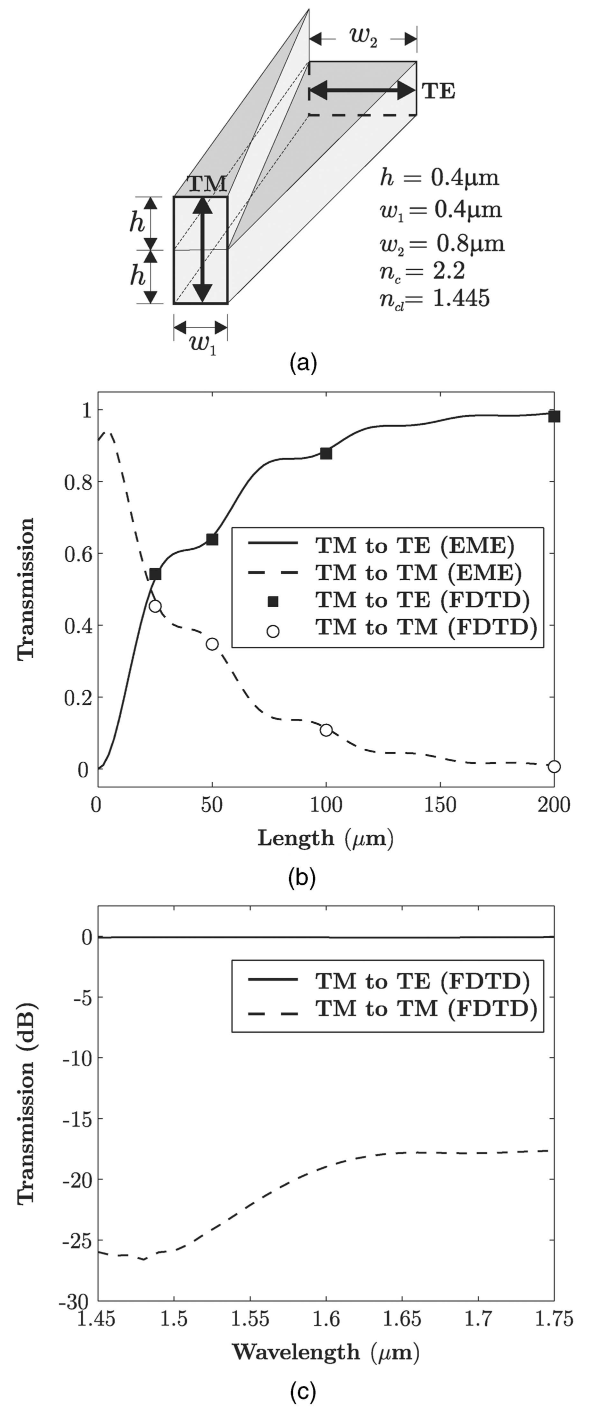

Fig. 1. (a) Polarization converter with tapering of the upper and lower core layers, (b) polarization conversion versus device length, (c) polarization conversion versus wavelength for a 200-μm-long device.

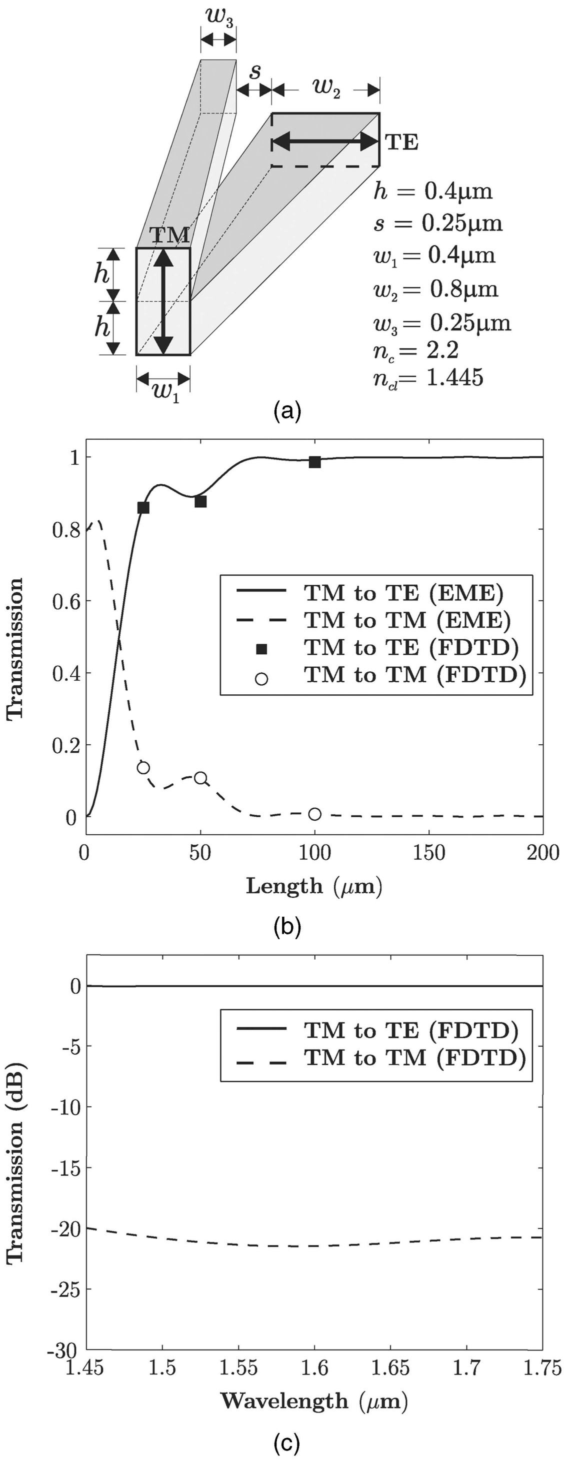

Fig. 2. (a) Polarization converter with tapering and separation of the upper and lower core layers, (b) polarization conversion versus device length, (c) polarization conversion versus wavelength for a 200-μm-long device.

The effect on propagation is similar to a pure tapering of the waveguide width. Results of FDTD and EME simulations as a function of length for the device in Fig. 2(a) are plotted in Fig. 2(b) for a wavelength of 1.55 μm. The wavelength dependence of a 100-μm-long structure as determined from a FDTD simulation is shown in Fig. 2(c). Again strong agreement is obtained between FDTD and EME results with no significant wavelength sensitivity or loss across the 1.45–1.75-μm band.

In conclusion, we have shown that polarization conversion can be achieved through mode evolution. An adiabatically twisted waveguide was approximated by use of a pair of waveguide core layers. The lower core layer was gradually widened along the length of the structure, whereas the upper layer was in one case tapered and in the other tapered and separated from the lower layer. FDTD and EME simulations verified the performance of the structures. In both cases efficient polarization conversion was demonstrated with no significant wavelength sensitivity across the entire 1.45–1.75-μm band for structure lengths of only 200 and 100 μm, respectively. These results are general. Although lower-index-contrast structures require longer transitions due to less-pronounced $\overline{\delta\beta}$'s, the qualitative behavior remains. Beyond a critical length, the length and wavelength dependencies are generally insignificant. Moreover, maintaining a large ratio of $\overline{\delta\beta}$ to $\overline{\kappa}$ does not require strict dimensional control. These are significant improvements over devices based on mode coupling.

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