Beam Propagation Analysis of Fast Mode-Conversion Evolution Bent Waveguides with Apexes-Linked Microprisms

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***Abstract*— A fast mode-conversion evolution and wide-angle low-loss abrupt bent waveguide with apexes-linked microprisms is proposed and compared with the conventional single prism structure. For the proposed bent waveguide with bend angle 10°, the transmitted power efficiency of 96.06% and a mode-conversion length of 40 μm can be achieved.**

***Index Terms*—Integrated optics, optical waveguide, waveguide bends.**

I. Introduction

A BENT waveguide is a very important element in integrated optics [1]. With a large angle waveguide bend, we can achieve high packing density and enough space on a substrate. However, its power loss significantly increases with a larger bend angle [2]. Recently, integrated microprisms were employed to reduce bending losses of the bent waveguides [3]–[5]. Nevertheless, due to the high prism index required in their design, mode-conversion originating a field mismatch of the guided modes between bent and straight waveguides must be taken into account. In general, to recover the irregular field distribution, the length of the bent waveguide has to be longer than that of the mode-conversion evolution. Therefore, for the design of compact electrooptical circuit with multiband branching waveguides [6], [7], both the wide bend angle and the required length of mode-conversion evolution need to be studied simultaneously. Recently, we reported that an ideal structure of a lossless bend can be approximated by a pair of apexes-linked microprisms (ALMP's) [8]. In this letter, the mode-conversion evolution of the ALMP's are investigated and compared with that of conventional microprisms. Not only the wide-angle low-loss performance is maintained, but the required length of the mode-conversion evolution is reduced.

II. Design and Simulation Method

Fig. 1(a) and (b) shows the schematic diagram of the conventional three-dimensional (3-D) micro-prism and our proposed ALMP abrupt bend waveguides on the air, respectively. Both bent waveguides can be fabricated by depositing different material with different refractive index for each section. In the ALMP design, the placement and the shape of the two prisms are deliberately considered. First, the angle $\alpha 1$ is chosen to be larger than $\alpha 2$ (i.e., $Lp_{11} > Lp_{12}$). Second, the apex of the ALMP is shifted from center $O(z_o, x_o)$ to a left-up point $O'(z_o + z_{\text{off}}, x_o + x_{\text{off}})$. Our design philosophy is that the light can leave the prism region as soon as possible with a shorter length Lp_{12} under the same prism length. Therefore, the process of the mode-conversion evolution would be shortened. But Lp_{12} must be long enough to direct the light into the bent waveguide after passing through the bent corner. Moreover, since the light must follow a curved path instead of an abrupt one when it travels through the bent region, the apex of the ALMP should be shifted from the center of the abrupt bent waveguide.

The simulation is carried out by the three-dimensional (3-D) fast Fourier transform beam-propagation method (FFT-BPM) [9]. The electric field $\mathcal{E}(x, y, z)$ can be assumed to be $E(x, y, z)\exp(-in_s kz)$ for a 3-D channel waveguide propagating in the z direction, where k and n_s are the free-space wavenumber and refractive index of the substrate, respectively. If its refractive index distribution is $n(x, y, z)$, the Helmholtz wave equation can be reduced as

$$2in_s K\frac{\partial E}{\partial z} = \frac{\partial^2 E}{\partial^2 x} + \frac{\partial^2 E}{\partial^2 y} + k^2\left[n(x, y, z)^2 - n_s^2\right]E. \qquad (1)$$

The electric field expression in (1) is found at each step by applying the split-operator FFT method. The electric fields at adjacent planes z and $z + \Delta z$ can be related by

$$E(z + \Delta z) = PQPE(z) \qquad (2)$$

where

$$P = \exp\left\{-\frac{i\Delta z}{4n_s k}\left(\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2}\right)\right\}$$
$$Q = \exp\left\{-\frac{in_s k\Delta z}{2}\left(\frac{n^2(x, y, z + \Delta z)}{n_s^2} - 1\right)\right\}.$$

In our analysis, the sampling windows of the simulation program is 128 × 128 pixels and the width of the analyzed domain is 90 μm. The space between transverse sampling

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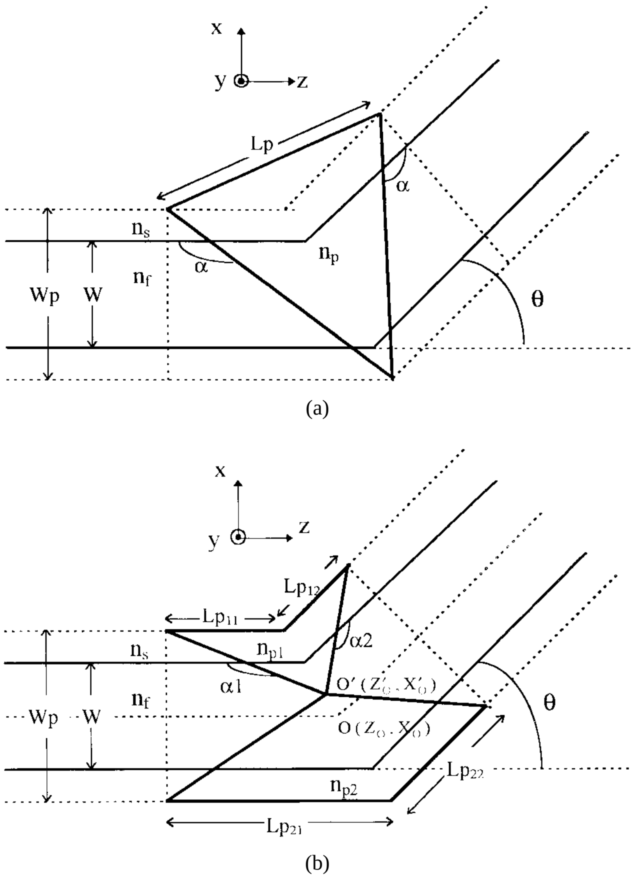

Fig. 1. Configuration of (a) a conventional abrupt bent waveguide with micro-prism and (b) a proposed abrupt bent waveguide with ALMP.

points is 90/128 ≅ 0.70 μm, and that the longitudinal sampling points is 0.25 μm. The total propagation distance is 160 μm.

III. Conclusion and Discussion

The bent waveguide under investigation is excited with the fundamental transverse electric (TE) mode (the wavelength is assumed to be 1.5 μm). The 3-D waveguide parameter values of the conventional micro-prism shown in Fig. 1(a) are: the waveguide width W and depth H are 9 and 9.6 μm, and the refractive indexes n_s and n_f of the substrate and the waveguide are 1.5 and 1.504, respectively. The micro-prism parameters calculated by reported formula based on the phase compensation rule [4] are: the prism length $Lp = 20$ μm, the width $Wp = 18$ μm, the depth $Dp = 10.2$ μm, and the refractive index $n_p = 1.7265$.

In our proposed ALMP design, shown in Fig. 1(b), the waveguide parameter values are the same as those in Fig. 1(a). The prism parameters, which are the simulated values we have made, are: the length $Lp_{11} = 16.55$ μm, $Lp_{12} = 9.3$ μm, $Lp_{21} = 17.14$ μm, and $Lp_{22} = 13.4$ μm, and the refractive indexes $n_{p1} = 1.6152$ and $n_{p2} = 1.3672$. The waveguide width Wp and depth Dp are 27 and 10.2 μm, respectively. The offsets of x and z axes are $x_{\text{off}} = 0.7$ μm and $z_{\text{off}} = -0.78$ μm, respectively.

By using the FFT-BPM analysis, the transmitted power efficiencies (η) of the conventional single-prism design and ALMP design based on the above mentioned parameter values

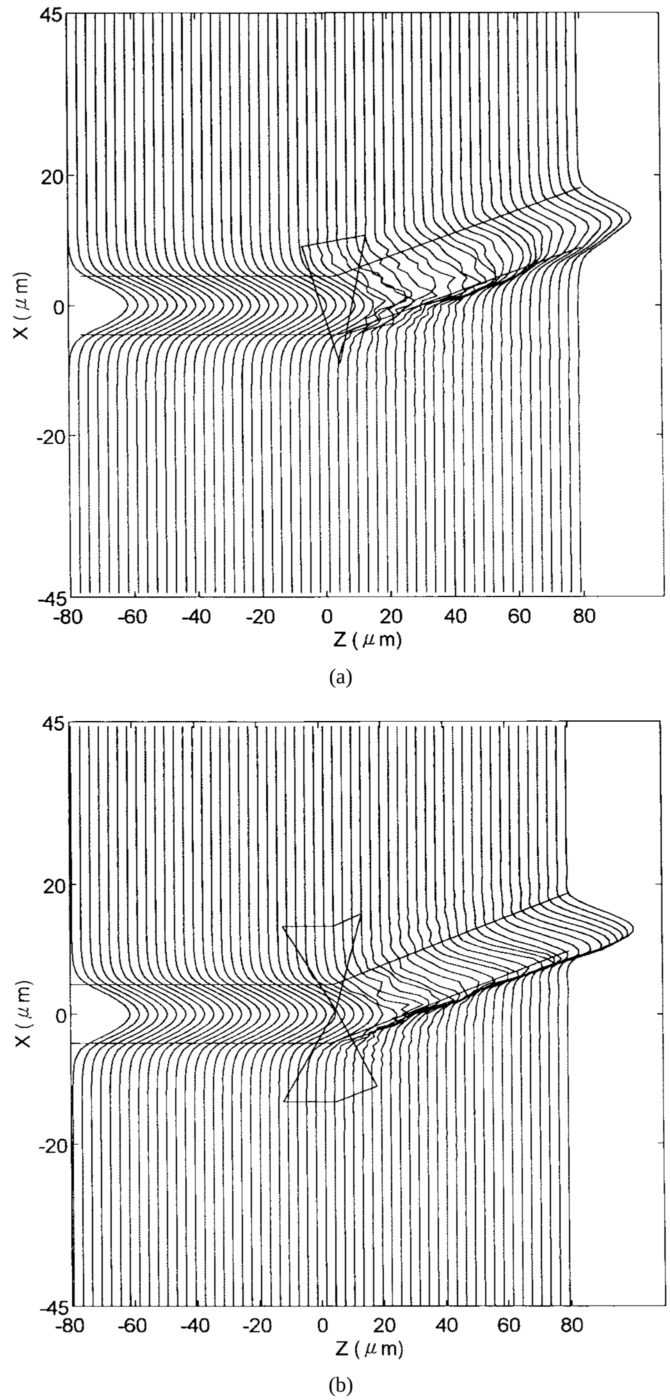

Fig. 2. Field intensity distributions in the bent waveguide ($\theta = 10^\circ$) of (a) micro-prism design (η = 95.64%) and (b) ALMP design (η = 96.06%).

and bend angle $\theta = 10^\circ$ are 95.64% and 96.06%, respectively. Their corresponding field intensity distributions on the waveguide surface of the propagating beam in the bent waveguide with bend angle of 10° are shown in Fig. 2(a) and (b) for the conventional micro-prism and ALMP, respectively. The output field distribution of the conventional micro-prism shown in Fig. 2(a) exhibits irregular distribution until at the propagating distance $z = 80$ μm. However, for the output field distribution of the ALMP shown in Fig. 2(b), the required length of the mode-conversion evolution is only $z = 40$ μm. This demonstrates that the mode-conversion evolution of the

ALMP is better than that of the conventional micro-prism design. Most of the optical field distribution of the eigenmode is seen to be more irregular near the bent corner due to the high index prism required in the conventional micro-prism design. In our ALMP design, the optical field of the eigenmode travels the less prism area and encounters the smaller index difference between the waveguide and prisms. Besides, with a larger prism width, less distortion is caused because most of the eigenmode field is directed into the bent waveguide. These are the main reasons the wide-angle low-loss performance as well as the fastening of the mode-conversion evolution in the proposed bent waveguide is achieved. Thus, a shorter abrupt bent waveguide with a low-loss output field can be designed.

In the letter, only the derived calculation parameters of ALMP, which are based on the curve propagation path and phase compensation rule, were used. To investigate the further performance of ALMP, the detailed design theory and physical mechanism will be described in future work. Moreover, the performance sensitivity to the variation in the physical dimension of distorted ALMP will be demonstrated.

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