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A GENERAL RULE FOR DESIGNING MULTIBRANCH HIGH-ORDER MODE CONVERTER

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Abstract—We propose a general rule that can be used to design multibranch high-order mode converters. We used the modal theory to analyze the proposed structure rigorously and presented the general principles. The well-established finite-difference beam propagation method was used to simulate the proposed device. The numerical results show that the proposed devices could really function as the all-optical mode converter device. It would be developed to quantify the applications and benefits in applications of optical signal processing and computing systems.

1. INTRODUCTION

In recent years, within the field of optical communications, there has been considerable interest in all-optical networks [1–3]. The advantages of all-optical networks are both the tremendous expansion of the bandwidth and the low end-to-end delay [4]. For all-optical networks, more and more attention now has been focused on the investigation of all-optical devices [5–7]. The multibranch waveguides are the key component in the applications of integrated optics. By coupling effect, the multibranch waveguides can be designed to operate as switches [8], wavelength-selective filter [9], and logic gates [10]. The design of mode converter [11–14] is another good guide for all-optical devices. Zhang et al. [15] experimented and fabricated a TE mode converter. Wu [16] had been made a novel multimode interference coupler with

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exponentially tapered waveguide. Kuo et al. [17] proposed the mode theory in metamaterial.

In this paper, we propose a general rule that can be used to design an all-optical high-order mode converter composed of a pair of multibranch optical waveguides with a sort-of hybrid combination. The high-order mode converter is a novel type of mode-controlling optical device structure based on multi-mode interference. A special case proposed in this paper is a ten-order mode converter for a multimode waveguide. The device would be used in the complement operation in all-optical data computing system. We use the modal theory [18–21] to analyze the proposed structure rigorously. For reducing the calculational processes, we presented the general design principles to study this structure. The well-established finite-difference time-domain beam propagation method (FD-BPM) [22–24] was used to simulate the proposed device. The numerical results show that the proposed devices could really function as the all-optical mode converter.

2. ANALYSIS

In this section, we had used the multibranh waveguide to construct a quality all-optical high-order mode converter. This mode converter can be used to transform the order of the input modes into the desired mode-order in a multibranch waveguides. The multibranch waveguide can be divided into three sections from bottom to top: the straight-line section (three-layer waveguide), the coupled separating-waveguide section (multilayer waveguides with interaction layers), and the isolated separating-waveguide section (multilayer waveguides

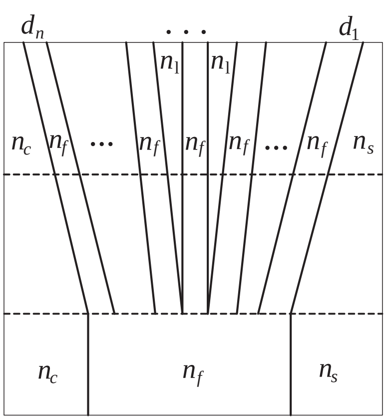


Figure 1. The structure of multibranch optical waveguide.

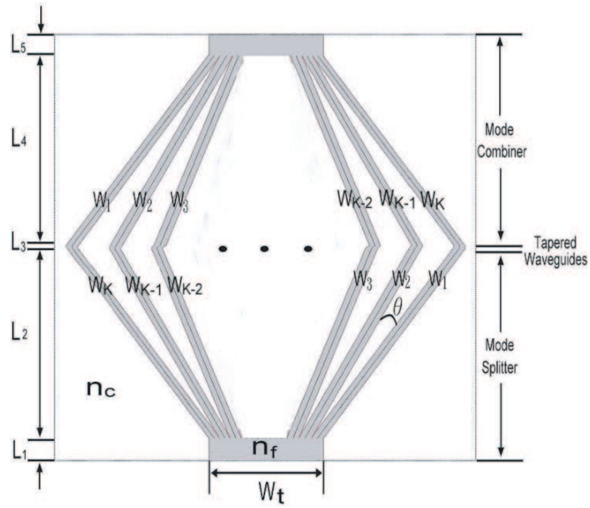


Figure 2. The structure of high-order mode converter.

isolated from one another), as shown in Figure 1. The cladding and substrate layers are assumed to extend to infinity in the $+x$ and $-x$ directions, respectively. The major significance of this assumption is that there are no reflections in the x direction to be concerned with, expect for those occurring at interfaces. The separating-waveguide section can be approximated by straight waveguide segments step by step. These step-waveguide segments can be analyzed by the method proposed in Refs. [18–21].

Figure 2 shows the high-order mode converter. The mode splitter separates the input modes, and the mode combiner combines the separated modes. The role of the tapered waveguides located in the middle is to transform the shapes of mode profiles adiabatically. A simple and general rule had been presented under condition that each guiding channel of multibranch waveguide had a regular variation in width. The method combined the modal theory of multilayer planar optical waveguide with the effects of mode localization and adiabatic propagation. For simplicity, there are the same indices of refraction in the cladding, substrate and interaction layers. In this structure, the width of the widest channel W_0 must be satisfied the following inequalities:

$$K\left(K-1\right)\Delta W < 2W_0 < \frac{\lambda_0}{\left(n_f^2 - n_c^2\right)^{\frac{1}{2}}} \tag{1}$$

where λ_0 is the input wavelength, ΔW the channel-width difference, and K the branch number. Each guiding channel can be characterized by a given width $W_i = W_0 - (i-1)\Delta W$ $(i = 1, 2, 3, \ldots, K)$, and the sum of widths of all guiding channels can be written as:

$$W_t = \sum_{i=1}^{K} W_i \tag{2}$$

The effective design of ΔW must satisfy the condition that the ratio of W_t to W_0 is more than and tends toward $K-1$. A different uncoupled propagation constant in each guiding channel is an essential condition. Because all of the materials in this structure are linear media, the different uncoupled propagation constant in each guiding channel can be achieved by different widths or different refractive index. The branching angle θ between the each adjacent guiding channel are the same. The good approximation of branching angle has to be satisfied the following inequality:

$$\theta \leq \tan^{-1}\left[\frac{K \cdot \Delta W}{4.3\,(K-1) \cdot W_t}\right] \tag{3}$$

In multibranch waveguide, the final distances of each pair of adjacent guiding channels relate with uncoupled propagation constants of each guiding channel. The final distances D of each adjacent guiding channel can be calculated by mode theory [18–21]. The lengths of L_2 and L_4 can be determined by the branching angle and the final distances. For matching the condition of adiabatic propagation and avoiding significant intermode scattering, the branching angle has to be sufficiently small [14]. However, a very small branching angle will result in a huge structure of this device. The above principles had provided a simple and direct idea to design the all-optical high-order mode converter.

3. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we use the finite-difference beam-propagation method to simulate the electric field propagating along the mode converter. A special case of this structure had been examined in this work. Figure 3 shows the ten-order mode converter structure. The propagation phenomena of the signal beam propagating along the structure had been studied. Figure 4 shows the ten-order mode converter for a multimode waveguide. The numerical data have been calculated with the values: the input wavelength λ_0 =1550 nm, the guiding channel refractive index n_f =1.57, background refractive index $n_c = n_s = n_l$ =1.55, branching angle $\theta = 0.01°$, W_t =28.48 µm, W_0 =3.1µm,

$\Delta W = 0.056\,\mu\text{m}$, $L_1 = L_3 = 5\,\text{mm}$, $L_2 = L_4 = 45\,\text{mm}$, and $L_3 = 0.5\,\text{mm}$. The layers $M = 21$ in the separating-waveguide section. This device can be used to transform the order of the input modes into the desired mode-order in a multibranch waveguides. The input modes had been separated in mode splitter section, and the separated modes had been combined in mode combiner section. The input

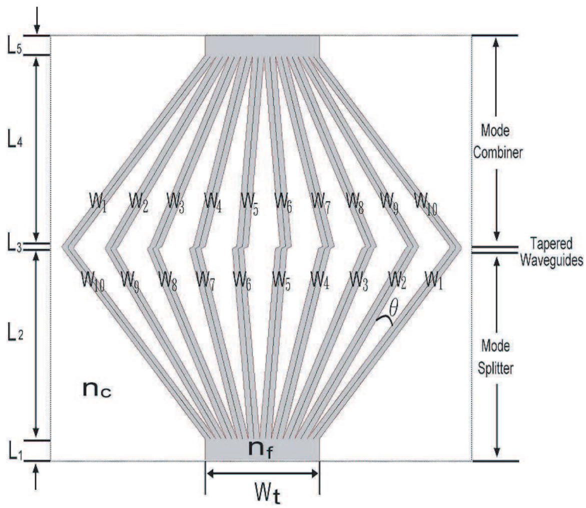
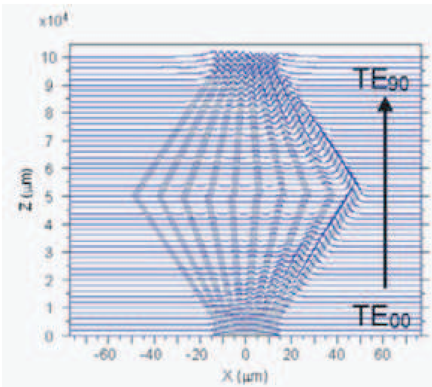


Figure 3. The structure of ten-order mode converter.

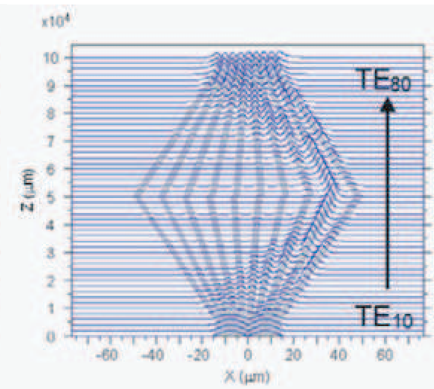
Table 1. The transmission efficiency P_0/Pi as a function of the ten-order mode converter.

Input signal	Output signal	P_0/P_i (%)
TE_{00}	TE_{90}	90.7
TE_{10}	TE_{80}	91.2
TE_{20}	TE_{70}	95.4
TE_{30}	TE_{60}	97.5
TE_{40}	TE_{50}	90.9
Input signal	Output signal	P_0/P_i (%)
TE_{50}	TE_{40}	90.5
TE_{60}	TE_{30}	97.6
TE_{70}	TE_{20}	96.9
TE_{80}	TE_{10}	97.1
TE_{90}	TE_{00}	98.2

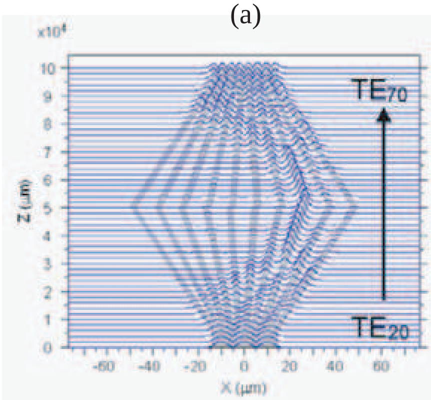
modes and output modes have the complement relations in this ten-order mode converter. Beam propagations shown in Figures 4(a)–(j) illustrate the mode converter operation. When the TE_{00} launched from the input waveguide section propagates along this structure, we



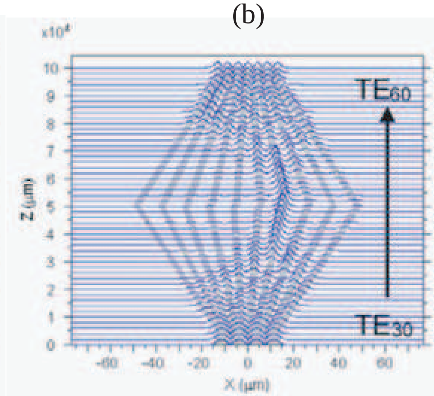
(a)



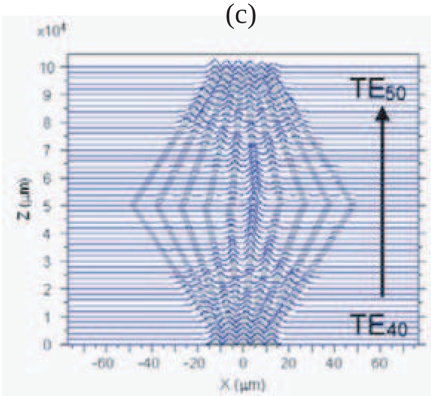
(b)



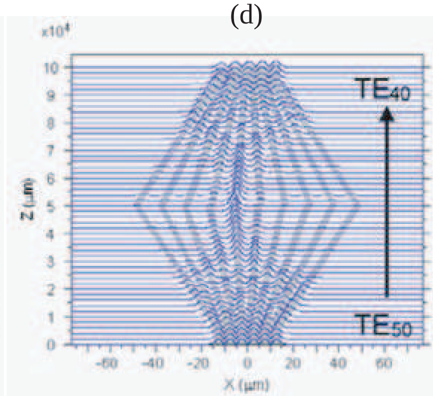
(c)



(d)



(e)



(f)

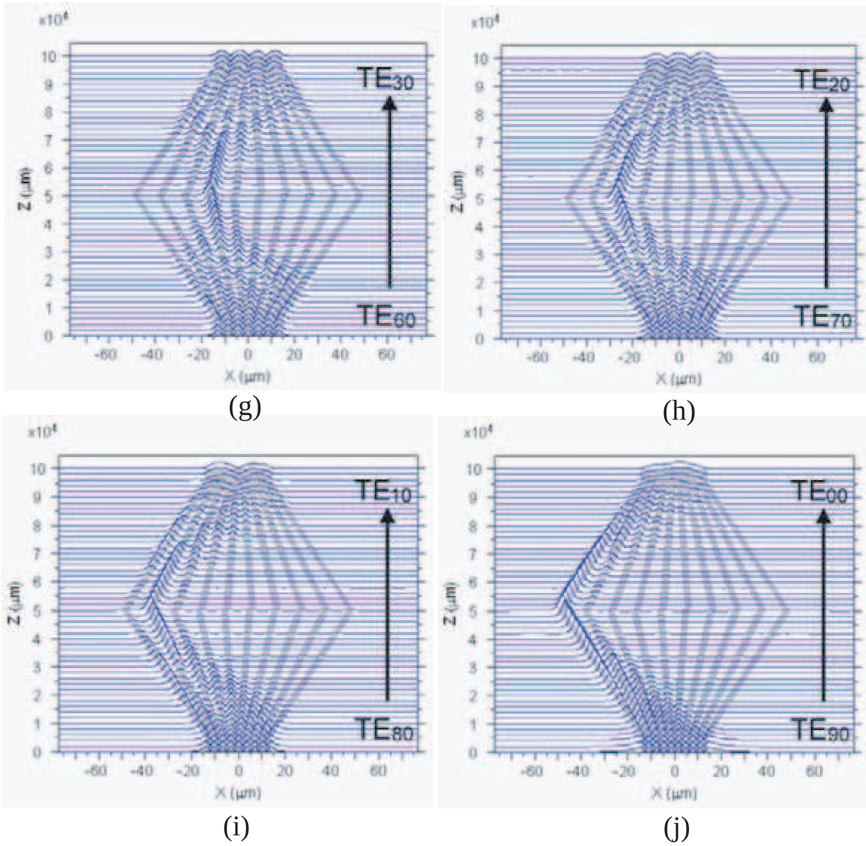


Figure 4. The mode converter operation of (a) $TE_{00} \rightarrow TE_{90}$, (b) $TE_{10} \rightarrow TE_{80}$, (c) $TE_{20} \rightarrow TE_{70}$, (d) $TE_{30} \rightarrow TE_{60}$, (e) $TE_{40} \rightarrow TE_{50}$, (f) $TE_{50} \rightarrow TE_{40}$, (g) $TE_{60} \rightarrow TE_{30}$, (h) $TE_{70} \rightarrow TE_{20}$, (i) $TE_{80} \rightarrow TE_{10}$, (j) $TE_{90} \rightarrow TE_{00}$.

can get a TE_{90} mode at output port, as shown in Figure 4(a). Also, a TE_{10} mode is converted into a TE_{80} mode, as shown in Figure 4(b); TE_{20} mode is converted into a TE_{70}, as shown in Figure 4(c); TE_{30} mode is converted into a TE_{60}, as shown in Figure 4(d); TE_{40} mode is converted into a TE_{50}, as shown in Figure 4(e); TE_{50} mode is converted into a TE_{40}, as shown in Figure 4(f); TE_{60} mode is converted into a TE_{30}, as shown in Figure 4(g); TE_{70} mode is converted into a TE_{20}, as shown in Figure 4(h); TE_{80} mode is converted into a TE_{10}, as shown in Figure 4(i); TE_{90} mode is converted into a TE_{00}, as shown in Figure 4(j). The transmission efficiency P_0/P_i (P_i the input signal power, P_0 the output signal power) of the input signal beam propagating throughout the output section is shown in Tab. 1. The numerical results showed that the transmission efficiency is very high, more than 90%. So all input modes of the given waveguide are converted in reverse older for the mode-older converter. The functional performance of this device would finish the complement operation in all-optical data computing system.

4. CONCLUSIONS

In this paper, we propose a general rule that can be used to design multibranch high-order mode converters. We used the modal theory to analyze the proposed structure rigorously and presented the general principles. A numerical example of the ten-order mode converter had been presented. The device would be used in the complement operation in all-optical data computing system. The numerical results show that the proposed devices could really function as the all-optical mode converter. It would be developed to quantify the applications in and be beneficial to ultra-high-speed and ultra-high-capacity all-optical data processing systems.

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