Compact Y-Branch Power Splitter Based on Simplified Coherent Coupling

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***Abstract*—Based on a simplified coherent coupling effect, a compact Y-branch power divider with polymer waveguides is presented. The simulated and measured normalized transmitted powers are 0.88 and 0.75 when the effective branching angle is as large as 19.7°. For the same transmission efficiency, both theoretical and experimental results show that the length required for the proposed Y-branch is shorter than those for the conventional S-bend configurations. Furthermore, the transmission spectrum shows that the proposed Y-branch is suitable for a dense wavelength-division-multiplexing application.**

***Index Terms*—Polymer waveguide, S-bend, simplified coherent coupling multisectional bends, Y-branch.**

I. INTRODUCTION

Y-BRANCH waveguides are important passive devices in optical integrated circuits and have been widely used in power splitters, optical switches, and Mach–Zehnder modulators. However, the conventional Y-branch suffers severe radiation loss when the branching angle is larger than 2° [1]. To reduce the radiation loss, the branching angle must be small and the device length is therefore increased. Recently, high-density optical circuits have become of interest. In order to increase the density of optical components on the same chip, developing a low-loss Y-branch waveguide with a large branching angle is of great significance. Several efforts have been made to overcome the loss problem, especially when the branching angle is large [2], [3]. Adding a microprism at the junction is one of the possible approaches. The function of the microprism is to compensate the phase mismatch caused by branching to reduce the radiation loss. However, the fabrication process is quite complicated which suffers from misalignment of the microprisms at the junction.

Low loss bending has been easily achieved by utilizing coherently coupled bends [4]. To fabricate the bends, only one photolithographic step is required, which greatly simplifies the fabrication process. Recently, Su and Wang [5] proposed a multisectional bending waveguide based on the simplified coherent coupling effect. This novel bend not only has higher transmission efficiency, but also has more compact size than the conventional one.

As for the choice of materials, polymer is attractive due to its advantages, such as ease of fabrication, low optical loss, high thermal stability, and low cost. Additionally, polymer waveguide processing is compatible with a variety of semiconductor materials.

In this letter, a polymer Y-branch power splitter with simplified coherently coupled multisectional bends is presented. The simulated and experimental results show that the proposed Y-branch has higher transmission efficiency and more compact size than the Y-branch with S-bend configurations. Furthermore, wavelength characteristics in the range of 1.52–1.62 μm are also reported.

II. WAVEGUIDE FABRICATION

The waveguide material used in this letter is benzocyclobutene (BCB). This polymer has a glass transition temperature of over 350 °C, so it has been widely used for flat-panel display, interlayer dielectrics, and microelectronics packaging applications. Here, BCB rib waveguides are fabricated by conventional photolithographic and the dry etching process. For convenience, a silicon wafer is used as the substrate. To fabricate the waveguide, a 4-μm-thick SiO_2 was grown on the substrate to form the lower cladding layer. A layer of BCB was then spin-coated on top of the lower cladding layer as the core layer. The thickness of the core layer can be changed by adjusting the speed of the spinner. Note that the lower cladding layer must be thick enough to prevent light in the core layer from being coupled into the silicon substrate. Right after the core layer was spun, thermal curing was carried out at 250 °C for 1 h in a nitrogen-flowing quartz tube. This step is to polymerize the film that also increases its chemical resistance.

As the rib waveguide pattern is often achieved by reactive ion etching, a thin SiO_2 film was deposited on the BCB layer as the hard mask. The waveguide pattern was then transferred onto the BCB layer using reactive ion etching in an $O_2 : CHF_3$ $(4:1)$ environment. The residual SiO_2 mask was removed in a diluted HF solution. As a result, the waveguide height and slab height are 2 and 0.8 μm, respectively. The width of waveguide is 2 μm. The refractive indexes of BCB and SiO_2 at the wavelength 1.55 μm are 1.535 and 1.446, respectively. Under these conditions, the waveguide supports a single mode. In this letter, the propagation loss of a straight rib waveguide was measured by the cutback method. The average propagation loss at 1.55 μm was found to be 0.87 dB/cm.

III. DESIGN AND EXPERIMENTAL RESULTS

Coherent coupling effect among closely spaced abrupt bends was originally described by Taylor for the analysis of power

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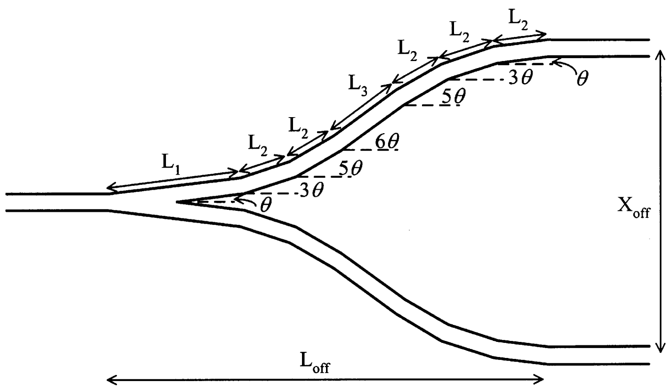
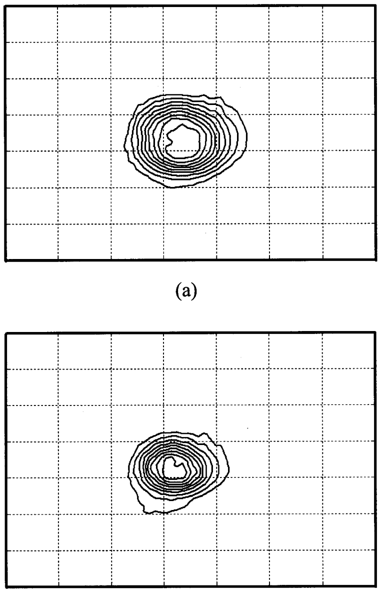


Fig. 1. Multisectional Y-branch based on simplified coherent coupling.

exchange between guided and radiation modes at the corner of the bend, [4], [6]. An abrupt bend generates a radiation field that interacts with the guided mode. As a result, the phase front of the total field rocks while the intensity is almost unchanged. The transmission efficiency is maximum when the phase front is perpendicular to the propagation direction of the output segment. A large bending angle can be achieved by coherently coupled multisectional bends [7]. In [5], a multisectional bending waveguide based on the simplified coherent coupling effect is proposed. It is found that transmission is unchanged if the segments without phase-front rocking are omitted. Then, for a constant total bending angle, the length of the device can be reduced. This idea is introduced here to produce the low-loss compact Y-branch. A schematic diagram of the proposed Y-branch is shown in Fig. 1. The complete Y-branch consists of a straight input waveguide, a branching structure, and two parallel output waveguides. Between input and output waveguides, the branching structure consists of two identical multisectional bends jointed at one end, as shown in Fig. 1. Each multisectional bend is formed by a sequence of waveguide segments of bending angles $\theta, 3\theta, 5\theta, 6\theta, 5\theta, 3\theta$, and θ. Because of the coherent coupling effect, segment lengths L_1, L_2, and L_3 are the parameters have to be optimized. The design of proposed Y-branch was based on the characteristics of BCB rib waveguide described in Section II. Assume the waveguide is excited by a transverse-electric (TE) eigenmode at 1.55 μm, and the evolution of optical power along the device is calculated by using a commercially available beam propagation method software. When $\theta = 3^\circ$, the optimal values for L_1, L_2, and L_3 are 39, 21, and 28 μm, respectively. With these optimal values, the separation of output waveguides X_{off} is 58.5 μm, and the branching length measured from input waveguide to output waveguides L_{off} is 168.6 μm. Thus, the effective full branching angle, defined as

$$\theta_{\text{eff}} = 2 \times \tan^{-1}\left(\frac{X_{\text{off}}/2}{L_{\text{off}}}\right) \tag{1}$$

is 19.7°. The device was tested by launching a TE-polarized laser light of wavelength 1.55 μm to the input end and detecting the power by a photodetector or an infrared camera at the output end. The field contours detected by the infrared camera are plotted, as shown in Fig. 2. The propagation loss of BCB rib waveguide at a 1.55-μm wavelength is 0.87 dB/cm. The simulated and measured normalized transmission efficiencies are 0.88 and 0.75, respectively. Note that the measured normalized transmission efficiency was obtained by comparing the total output power through the Y-branch with that through the straight waveguide. In addition, we also characterized the performance of the device for the transverse-magnetic (TM) polarization. The simulated and measured normalized transmission efficiencies are 0.87 and 0.72, respectively. The transmission efficiencies for the TM polarization are slightly lower than those for the TE polarization. As a result, this power splitter is expected to provide a little polarization dependence.



(a)

(b)

Fig. 2. Output contours of proposed Y-branch (a) left arm and (b) right arm.

TABLE I
NORMALIZED TRANSMITTED POWER OF FOUR TYPES OF Y-BRANCH STRUCTURES

Structure	**Normalized transmitted power**	
	Simulation	**Experiment**
Proposed Y-branch	**0.88**	**0.75**
Circular S-bend	**0.83**	**0.7**
Cosine S-bend	**0.83**	**0.67**
Sine S-bend	**0.79**	**0.62**

IV. DISCUSSION

In general, a Y-branch with straight angle arms will make the device long. A much more compact Y-branch can be designed by introducing S-bend configuration instead of angled-bend configuration in the arrangement. With $X_{\text{off}} = 58.5$ μm and $L_{\text{off}} = 168.6$ μm, the performance of the proposed Y-branch is compared with those of three Y-branches with S-bend configurations, as listed in Table I. Obviously, both simulated and experimental results have shown that the proposed Y-branch has the highest transmission efficiency. Fig. 3 shows the transmission efficiencies versus the branching length with $X_{\text{off}} = 58.5$ μm for our device and three Y-branches with S-bend configurations. For an acceptance of 88% efficiency, the branching lengths of Y-branch with circular S-bend, cosine S-bend, and sine S-bend configuration are 184, 187, and

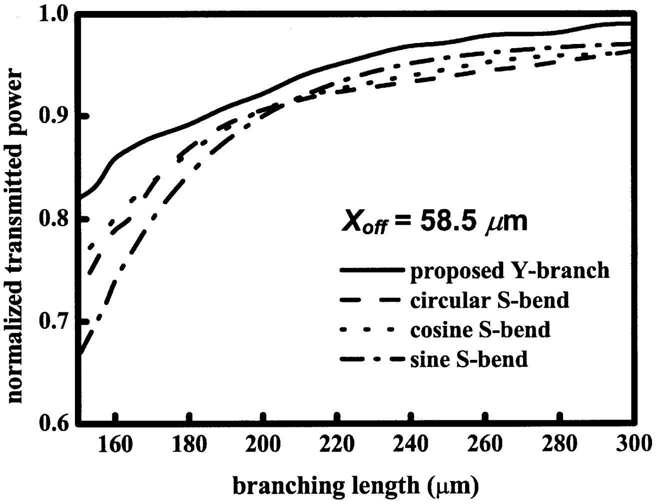


Fig. 3. Normalized transmitted power versus the branching length for proposed Y-branch and three Y-branches with S-bend configurations.

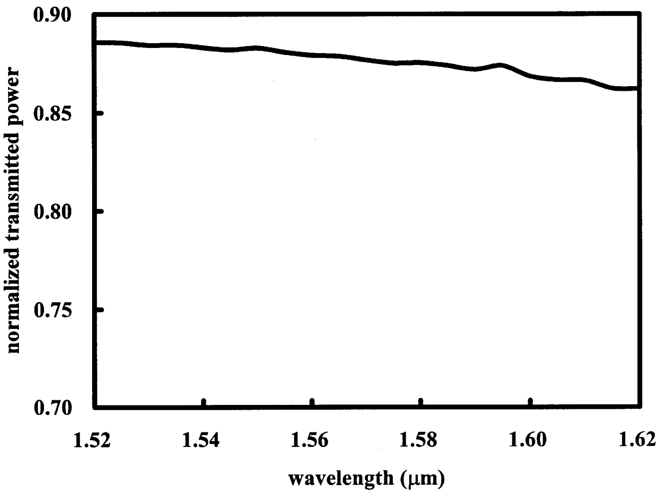


Fig. 4. Transmission spectrum of proposed Y-branch.

192 μm, respectively. These lengths are longer than the length of the proposed Y-branch that is 168.6 μm. Thus, it can be concluded that the proposed Y-branch has the advantages of both higher transmission and shorter length.

As the conventional Y-branch structure is wavelength insensitive and widely used for dense wavelength-division- multiplexing optical communication systems [8], the wavelength response of the proposed Y-branch was characterized for comparison. The wavelength window for optical communication covers C-band and L-band, i.e., in the range of 1.528–1.620 μm. Fig. 4 shows that the proposed Y-branch has a flat transmission efficiency varying from 0.88 to 0.86 in the wavelength range between 1.52 and 1.62 μm. Although the device is designed for operation at 1.55 μm, it still works well at other wavelengths near the operating wavelength. Thus, the proposed Y-branch structure can be considered wavelength insensitive, though the transmitted power at longer wavelengths is slightly smaller due to its weaker optical confinement.

V. CONCLUSION

Large-angle BCB polymer Y-branch power splitters based on simplified coherently coupled multisectional bends have been successfully fabricated. The BCB rib waveguide has a propagation loss of 0.87 dB/cm at the wavelength 1.55 μm. With an effective full branching angle of 19.7°, the proposed Y-branch has higher transmitted power than Y-branches with S-bend configurations. Also, comparing Y-branches with S-bend configurations, for the same 88% efficiency, the length of the proposed Y-branch is the shortest. In addition, we have shown that the proposed Y-branch is almost wavelength independent in the range of 1.52–1.62 μm. Details of the application of the proposed Y-branch structure on integrated optical devices, such as $1 \times N$ power splitters and switches, will be of great interests in the future.

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