JOURNAL OF OPTOELECTRONICS AND ADVANCED MATERIALS Vol. 9, No. 7, July 2007, p. 2133 - 2137

Cost effective polymer optical couplers based on multimode interference techniques

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Weakly guiding Multimode Interference (MMI) optical splitters and cross couplers based on photodefinable BenzoCyclobutene (BCB 4024-40) polymer are presented for the first time. The devices are designed based on three interference mechanisms of MMI and fabricated on BK7 glass substrate with a thin layer of SiO_2 as cover. A cost effective chemical etching technique is used in the fabrication process to take advantage of the photosensitive nature of the polymer. The waveguide loss is measured using the cut-back method to be 3.5 dB/cm. The fabricated symmetric power splitters are found to exhibit 0.15-0.51 dB splitting uniformity with maximum recorded insertion loss of 1.13 dB. Meanwhile, the 2×2 cross couplers are testified to demonstrate a maximum crosstalk of -17.81 dB and maximum loss of 3.37 dB.

(Received May 30, 2007; accepted June 27, 2007)

Keywords: BenzoCyclobutene polymer, Multimode interference, Optical coupler, Chemical etching technique, Polymer optical waveguide

1. Introduction

Since its brief introduction by Soldano and Pennings [1], Multimode Interference (MMI) effect has gained widespread usage in optical interconnect applications such as power coupling, switching and wavelength multiplexing, particularly due to its broad advantages such as compactness, polarization insensitivity and large fabrication tolerances [1]. In addition, the advent of high speed and high capacity Wavelength Division Multiplexing (WDM) network has further requires the optical interconnection devices to have large optical bandwidth and compact in size for possible integration, which has relatively speed up its application.

However, most of these MMI based interconnection devices have so far been fabricated in high index contrast materials such as optical switch in Mach-Zehnder Interferometer (MZI) in InGaAsP/InP [2], optical switch in GaAs/AlGaAs [3] and couplers in silicon-on-insulator [4]. This is due to conventional thoughts [5] that waveguides exhibiting weak guiding as a result of low index contrast materials cannot produce efficient MMI devices.

Yet, it has been proved by Fardad and Fallahi [6], that the low index contrast materials system can be efficiently applied in the development of MMI based devices. They have successfully demonstrated 1×32 MMI power splitters with excellent properties through the use of sol gel material on silica. Following this, a work on polymer based MMI interconnection devices have been arose significantly, such as work on splitters by Mule' et. al., [7]; Rabus et. al., [8] and optical switch by Fan Wang et.al., [9].

Undoubtedly, the observed scenario deeply requires more research contributions in the development aspects of polymer based MMI interconnection devices. Appreciably, in research for cost effective optical interconnections with desired optical performance for current and future high speed and high capacity network, a cost-effective photodefinable polymer and MMI effect on coupling devices are one of the potential candidates. In this paper, we show the ability of organic BenzoCyclobutene (BCB 4024-40) polymer from Dow™ [10] as an extremely low-cost optical material for fabricating weakly guiding MMI interconnection devices, using splitters and cross couplers as demonstrators.

2. Material and device design

BenzoCyclobutene (BCB 4024-40) polymer is photodefinable with similar properties to a negative photoresist, hence the material can be exposed directly to define the waveguide and the process does not require any plasma or reactive ion etching, enabling simple devices to be fabricated easily. In order to characterize for material properties, thin films of BCB 4024-40 forming slab waveguides were fabricated on BK7 glass substrate by spin-coating at speeds ranging from 1500 to 6000 rpm. The slab waveguides were then measured for the average refractive index and film thickness using prism coupling method [11]. To characterize the slab loss, the fiber probe method is applied in which the fiber is moved along the slab to measure the power [12]. Fig. 1 shows the relation between coating speed and polymer slab thickness. The average refractive index obtained is 1.5556 for TE polarization and the average value of slab loss is measured to be 1.01 dB/cm. Evidently, this shows the BCB 4024-40's ability in optical guiding application, which shall be further manipulated to take advantage of the cost-effective nature of the polymer.

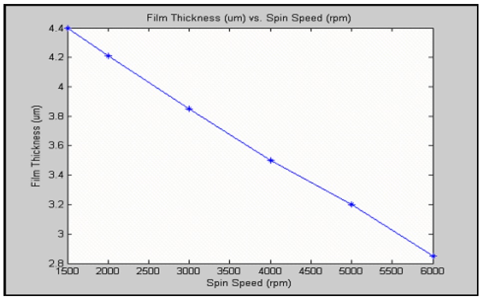


Fig. 1. Relation between polymer film thickness and coating speed.

MMI couplers work on the principle of self-imaging effect, a property of multimode waveguides by which an input field is reproduced in single or multiple images at periodic intervals along the propagation direction of the guide, as a result of constructive interference between the modes [1]. Accordingly, there are two possible types of self imaging mechanism, *General Interference* (GI) and *Restricted Interference* (RI). The RI scheme can be divided into paired interference and symmetric interference.

In GI, all modes are excited in the MMI section and constructive interference occurs at:

$$z = p(3L_\pi) \tag{1}$$

where L_π, known as the beat length is defined by:

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4nW_e^2}{3\lambda_0} \tag{2}$$

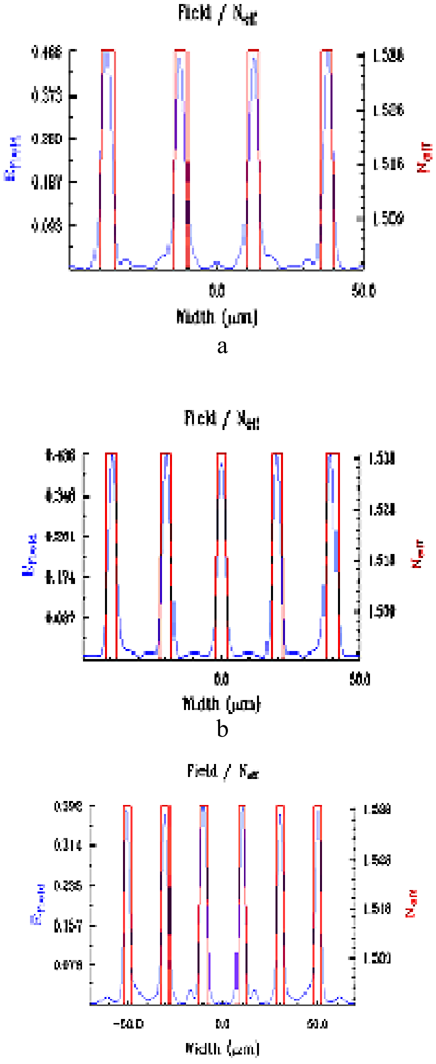
β_0 and β_1 are propagation constants of the fundamental and the first order lateral modes, respectively, λ_0 is a free-space wavelength, n is the effective index and W_e is the effective width of the multimode waveguide. When p is even, the output is a direct image of the input field and when p is odd it is a mirrored image. In contrast, by placing the input access waveguides at 1/3 or 2/3 of the MMI section width, the resonant images will occur at:

$$z = p(L_\pi) \tag{3}$$

This mechanism is called paired interference of RI type. Note that this scheme allows the design to be three times shorter compared to GI. In the special case where the odd modes are not excited in the multimode waveguide, a symmetric interference of RI can be obtained which are linear combinations of the symmetrical even modes. This condition can be achieved by centre-feeding the multimode section and the N fold output images are obtained at distances:

$$z = \frac{p}{N}\left(\frac{3L_\pi}{4}\right) \tag{4}$$

In this paper, two types of MMI couplers have been considered namely, splitters and cross couplers. The symmetric interference mechanism has been considered for 1×4, 1×5 and 1×6 splitters' architectures with MMI width of 100 μm, 100 μm and 120 μm, respectively. 2×2 cross couplers' designs are based on general and paired interference mechanism of MMI, considering width of 50 μm and 70 μm, respectively. The devices are based on a ridge structure of BCB 4024-40 polymer on BK7 glass as a substrate and a thin layer of SiO_2 as upper cladding. A combination of effective index method [13] and two-dimensional beam propagation method (2D-BPM) from Optiwave is employed for the analysis. The fields at the output of these splitters and cross couplers using the 2D-BPM analysis are shown in Figs. 2 and 3 respectively. These simulations show good uniformity and acceptable crosstalk level, which further justify the fabrication of weakly guiding MMI splitters and cross couplers, based on photodefinable BCB 4024-40 polymer.

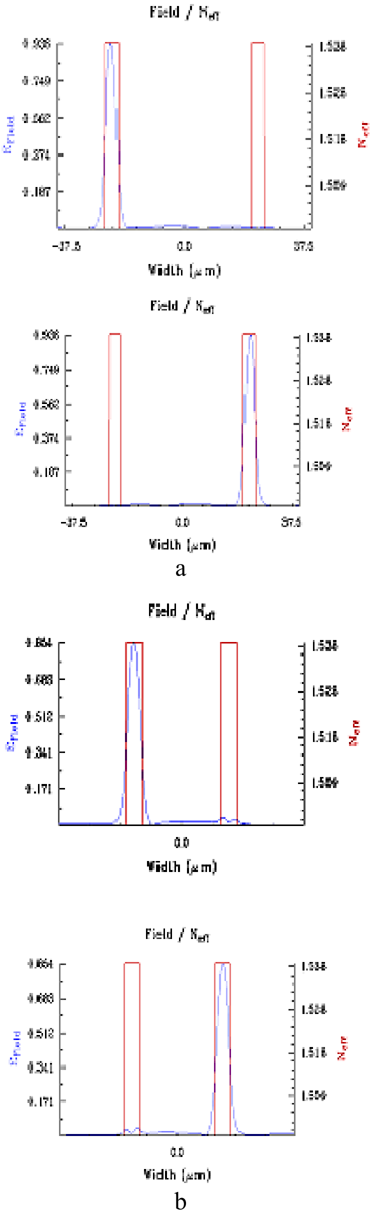


a

b

c

Fig. 2. 2D-BPM analysis of (a) 1×4, (b) 1×5, (c) 1×6 optical splitters.



a

b

Fig. 3. 2D-BPM analysis of 2×2 cross coupler based on (a) general interference, (b) paired interference.

3. Device fabrication

The process for the fabrication of MMI couplers using BCB 4024-40 is similar to a thin film multi-chip module process. According to our previous simulation [13], to produce a single-mode waveguide using this material structure, the core thickness needs to be about 4 μm. Hence, the coating speed of 3000 rpm and 4 μm of mask opening are chosen to realize a single-mode square structure.

In order to maintain good adhesion with the BK7 substrate layer, AP3000 adhesion promoter was spin coated on the substrates before polymer coating. After the polymer was spin coated, the film was heated on a hotplate for a specific time and temperature to drive out the residual solvent. The time and temperature depend on the film thickness such as to prevent film wrinkle. This is followed by the photolithography step which is the process of transferring the two-dimensional patterns on the photomask to the polymer film. As the BCB 4024-40 is a negative acting polymer, a dark field mask was utilized. A mask aligner having I-line UV exposure at 365 nm wavelength was used to crosslink the exposed polymer region. The mask aligner power density was set to 3mW/cm^2 and the exposure time was 20 seconds.

After exposure, a pre-develop bake was carried out to increase the etching resistance and film adhesion to the substrate. The pre-develop bake temperatures were 10^{0}C lower than the pre-exposure bake. The chemical etching or developing process of BCB 4024-40 polymer requires the puddle development process. In this process, a DS2100 developer solvent was dispensed onto the sample surface. After 30 seconds of puddle time, sample was then rinsed for 10 seconds and spun at high speed to remove the developer solvent. To further dry the film and stabilize the side wall, the sample was baked on a hot plate immediately after developing. Finally, the sample was cured in a box oven at 250^{0}C to remove the residual solvents and harden the polymer. At the end of the process only the masked areas remain which form the devices. Note that neither photoresist nor RIE or plasma etching is necessary. However, the drawback of this chemical etching method is reduced quality of sidewall resolution of the waveguide [10].

In order to reduce the refractive index difference between the waveguide core and the surrounding, a one-micron thick layer of SiO$_2$ was deposited on top of the polymer using plasma enhanced chemical vapour deposition (PECVD) technique. The deposition process was carried out at 60^{0}C for one hour. Finally, the waveguide sample was polished at the facets for optical coupling.

4. Results and discussion

Images of the fabricated optical splitters and cross couplers are shown in Figs. 4 and 5, respectively. The photopatterned devices exhibit smooth polished end facets but significant sidewall roughness. The roughness is presumably due to minor corrugation at the mask opening.

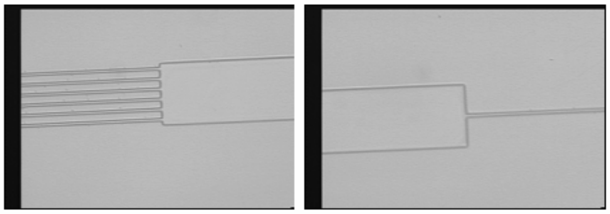


Fig. 4. Microscope images of fabricated MMI splitters

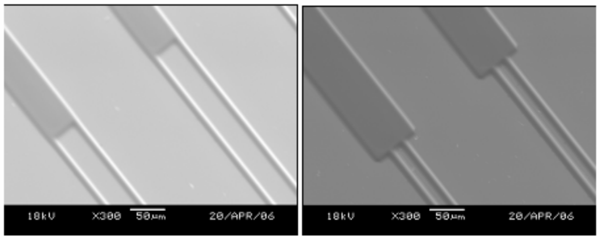


Fig. 5. SEM images of fabricated MMI cross couplers

For single mode waveguide and couplers measurements, a single-mode fibre is used to couple 1550-nm laser source into the polished end facet of the access waveguide. The output is measured using a Germanium (Ge) photodetector and the near field profile is imaged onto an infrared camera integrated with beam analyzer software.

The waveguide loss was measured with the conventional cut-back method. The results, given in Fig. 6, show that the propagation loss of the BCB waveguides is 3.5 dB/cm and the coupling loss is 10.5 dB. The relatively high propagation loss is presumably due to scattering from the sidewall roughness. The high value of coupling loss is mainly due to the size mismatch between the fibre and the waveguide modes.

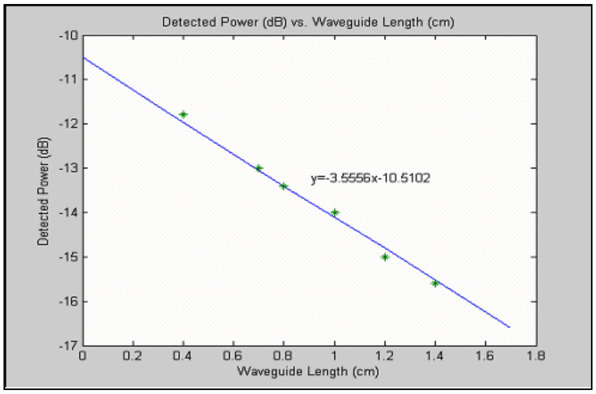


Fig. 6. Measured output power for several waveguide lengths.

The images of the output beams for the fabricated splitters are shown in Fig. 7. Meanwhile, the measurement results of devices' insertion loss and imbalance are tabulated in Table 1. For cross couplers, the images of measured output beams are shown in Fig. 8 and the measurement results of devices' insertion loss and crosstalk are tabulated in Table 2.

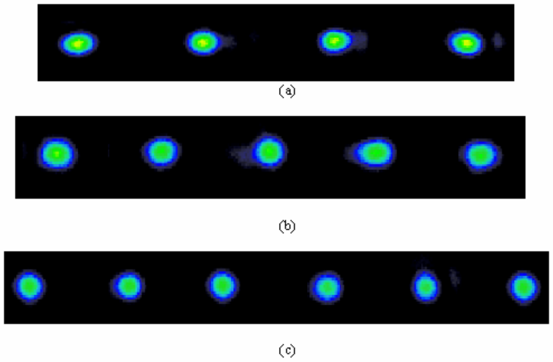


Fig. 7. Near field profile of the splitter outputs: (a) 1×4, (b) 1×5 and (c) 1×6.

Table 1. Measured insertion loss and imbalance for fabricated MMI splitters.

Splitter type	Imbalance (dB)	Insertion loss (dB)
1×4	0.15	0.94
1×5	0.31	1.01
1×6	0.51	1.13

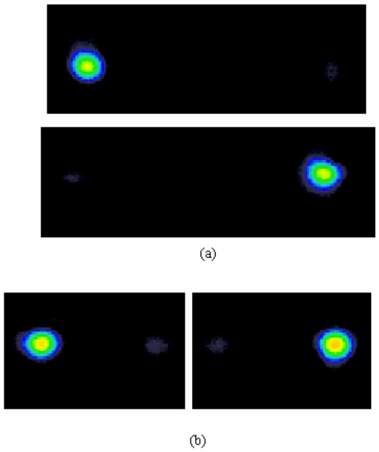


Fig. 8. Near field profile of 2×2 cross coupler outputs: (a) general, (b) paired.

Table 2. Measured insertion loss and crosstalk for fabricated MMI cross couplers.

Cross coupler type	Insertion loss (dB)	Crosstalk (dB)
2×2 (general interference)	3.37	-23.52
2×2 (paired interference)	2.55	-17.81

The results show that the MMI splitters exhibited excellent imbalance and insertion loss condition. In addition, the fabricated cross couplers also demonstrated excellent crosstalk level, but significant increases in insertion loss are recorded. Nevertheless, these primary results confirm the availability of MMI based couplers and devices in highly cost effective photodefinable polymers. It is strongly believed that further improvements in design, fabrication and characterization aspects will increase the device performance.

5. Conclusions

We have successfully demonstrated series of MMI splitters and cross couplers, fabricated in photosensitive BenzoCylobutene (BCB 4024-40) polymer. Interestingly, this low cost development on BK7 glass substrate using only chemical etching and standard photolithography, without the need for plasma etching facilities. However, due to the quality of photomask, the resulting sidewall roughness yielded a relatively high propagation loss of 3.5 dB/cm. At 1550 nm wavelength, the symmetric MMI splitters exhibited excellent performance with measured imbalance of 0.15-0.51 dB and maximum measured insertion loss of 1.13 dB. For 2×2 cross coupler, the general interference based structure demonstrated an insertion loss of 3.37 dB with -23.52 dB of crosstalk level. On the other hand, a cross coupler which is based on paired interference mechanism exhibited higher crosstalk level of -17.81 dB but smaller insertion loss of 2.55 dB. These results provide confidence on the development of MMI based devices in cost-effective photodefinable polymer and further improvements on the development processes will definitely increase the device performance.

Acknowledgment

The authors wish to thank Mee-Koy Chin, Shuh-Ying Lee and Chee-Wei Lee of Nanyang Technological University (NTU), Singapore for their help in this development process. The authors wish to thank the Ministry of Science, Technology and Innovation of Malaysia (MOSTI) for funding this research work and special thanks to Dow™ for supplying the polymer.

References

[1] L. B. Soldano, E. C. M. Pennings. Journal of Lightwave Technology. **13**(4), 615 (1995).
[2] L. B. Soldano, A. H. de Vreede, M. K. Smit, B. H. Verbeek, E. G. Metaal, F. H. Groen. IEEE Photonics Technology Letters. **6**(3), 402 (1994).
[3] R. M. Jenkins, J. M. Heaton, D. R. Wright, J. T. Parker, J. C. H. Birbeck, G. W. Smith, K. P. Hilton. Applied Physics Letters. **64**(6), 684 (1994).
[4] X. Jin Song, Y. Jin Zhong, F. Zhong Chao, W. Zhang Tao, C. Shao Wu. Chinese Physics Letters. **21**(1), 104 (2004).
[5] B. R. West, S. Honkanen. Optics Express. **12**(12), 2716 (2004).
[6] M. A. Fardad, M. Fallahi. IEEE Photonics Technology Letters. **11**(6) 697, 1999.
[7] A.V. Mule', R. Villalaz, T. K. Gaylord, J. D. Meindl. IEEE Photonics Technology Letters. **16**(11) 2490, (2004).
[8] D. G. Rabus, P. Henzi, J. Mohr. IEEE Photonics Technology Letters. **17**(3) 591 (2005).
[9] F. Wang, J. Yang, L. Chen, X. Jiang and M. Wang. IEEE Photonics Technology Letters. **18**(2) 421 (2006).
[10] The Dow Chemical Company. Product Literature: Cyclotene™ Advanced Electronic Resins, (1999).
[11] W. A. Pasmooij, P. A. Mandersloot and M.K. Smit. Journal of Lightwave Technology. **7**(1) 175 (1989).
[12] Nourshargh et. al. Electronics Letters. **21**(18) 818 (1985).
[13] Kassim et. al. RF and Microwave Conference Proceedings, Kuala Lumpur, 5-6 October 2004, 272, 2004.

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