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Optical cross couplers based on wet-etch processing of benzocyclobutene polymer

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ABSTRACT

In this paper, a characterization process of benzocyclobutene (BCB 4024-40) polymer and its realization into optical devices are described. By using the prism coupling technique, the polymer film thickness for various coating speed and the refractive index have been measured. Based on these results, the optical waveguides and couplers have been fabricated using the wet-chemical etch processing technique to take advantage of the photosensitive nature of the polymer. By adopting the multimode interference technique (MMI), the fabricated 2 × 2 optical cross couplers have been testified to demonstrate a maximum crosstalk of −17.81 dB and maximum loss of 3.37 dB.

1. Introduction

Integrated optics are having an increasing impact on the development of lightwave communication systems with applications such as high speed broadband switching and high speed interconnects for local area network. The main element that contributes to the performance of integrated optics is the waveguides/devices material. Of this, material research has been emerged continuously in order to support huge demand in the integrated optics research and development. Researches into polymer material for integrated optics have been started extensively since 1980s where various types of optical devices have been successfully developed. Undoubtedly, this major attraction to the polymer is due to their ability to be processed rapidly, cost-effectively and with high yields [1,2].

Since its brief introduction by Soldano and Pennings [3], 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 [3]. In addition, the advent of high speed and high capacity Wavelength Division Multiplexing (WDM) network has further requires the optical interconnects to have large optical bandwidth and compact in size for possible integration, which has relatively speed up its application.

Motivated from the broad advantages offered by polymer and MMI structure, work on polymer based MMI devices have been arose significantly such as work on splitters by Mule' et al. [4]; Rabus et al. [5]; Ibrahim et al. [6] and optical switch by Wang et al. [7]. Undoubtedly, more research contributions are deeply required in the development aspects of polymer based MMI interconnection devices.

In this paper, we will report on the development of MMI optical couplers based on benzocylobutene (BCB 4024-40) polymer from Dow™ [8]. This polymer is photodefinable where its negative acting properties allows the waveguides to be fabricated following steps similar to photoresist processing without the need for any plasma or reactive ion etching. A single-mode optical waveguide based on BCB 4024-40 polymer has been demonstrated successfully in our previous work [9]. The objective of this paper is to show the ability of BCB polymer in realizing a more complex optical device at lower manufacturing cost and acceptable optical performance.

2. Optical material and characterization

Photodefinable benzocyclobutene (BCB 4024-40) polymer is a wet-chemical etching based material in which the waveguide patterning process is less complex and lower at cost as compared to the dry-etching/plasma etching techniques. In this section, the polymer characterization result will be revealed. Although the same result has been published in [9], the findings will be repeated here for better understanding in the up-coming sections.

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

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6000 rpm. The slab waveguides were then measured for the average refractive index and film thickness using prism coupling method [10]. To characterize the slab loss, the fiber probe method is applied in which the fiber is moved along the slab to measure the power [11]. 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. Based on this, it clearly indicates that the BCB 4024-40 polymer is able to provide good optical guidance, which shall be further manipulated to take advantage of the cost-effective nature of the polymer. The obtained results will be used in the development process of an MMI optical cross couplers.

3. Coupler's design

The developed couplers in this paper are based on the working principle of Multimode Interference (MMI) effect. The effect is to be based on self-imaging mechanism in 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 [3]. Two types of self-imaging mechanism are possible for implementation, namely the General Interference (GI) and Restricted Interference (RI). The RI scheme can be divided into paired interference and symmetric interference. In this work, the GI scheme and the paired interference technique of RI scheme will be adopted.

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

$$z = p(3L_\pi) \quad (1)$$

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

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

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:

$$z = p(L_\pi) \quad (3)$$

This mechanism is called paired interference of RI type. Note that this scheme allows the design to be three times shorter compared to GI.

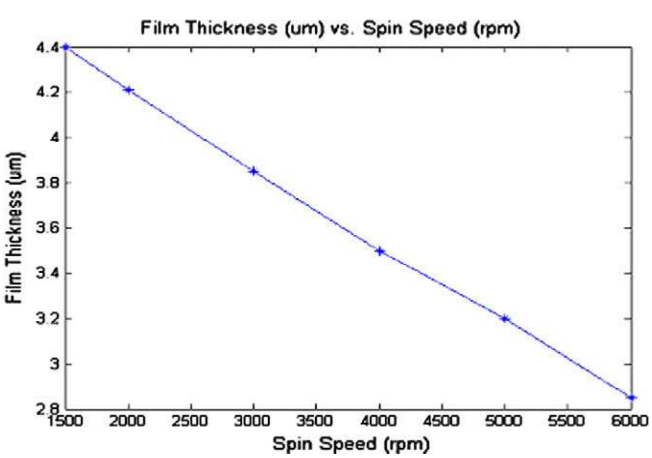

Fig. 1. Relation between polymer film thickness and coating speed.

2 × 2 cross couplers' designs are based on general and paired interference mechanism of MMI, considering width of 50 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 and two-dimensional beam propagation method (2D-BPM) from Optiwave is employed for the analysis. The fields at the output of these cross couplers using the 2D-BPM analysis are shown in Fig. 2. It can be observed from the simulation results that both devices show excellent performance in terms of crosstalk level. Inevitably, this proved the ability of BCB polymer to be used in the development of MMI cross couplers.

4. Device fabrication and characterization

The fabrication technique for this cross coupler is mirrored from our previous work in [9]. However, for clarity purpose, the steps will be repeated in this paper. 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 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 where 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 s. 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 °C lower than the pre-exposure bake. The chemical etching of BCB 4024-40 polymer requires the puddle development process where a DS2100 developer solvent was dispensed onto the sample surface. After 30 s of puddle time, sample was then rinsed for 10 s 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 °C to remove the residual solvents and harden the polymer. At the end of the process only the masked areas remain which form the waveguides. Note that neither photoresist nor RIE or plasma etching is necessary.

The scanning electron microscope (SEM) images of the fabricated cross couplers are shown in Fig. 3. The photopatterned waveguides exhibit significant sidewall roughness. The roughness is presumably due to minor corrugation at the mask opening. It was also observed that the cross section of the waveguides is not perfectly rectangular due to wet-chemical etching limitation together with diffraction effects associated with mask opening and film thickness. This agrees with other reported results based on chemical etching technique [12].

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 vapor 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.

5. Results and discussion

For couplers measurements, a single-mode fiber is used to couple 1550-nm laser source into the polished end facet of the access waveguide, by means of butt-coupling technique. The output is

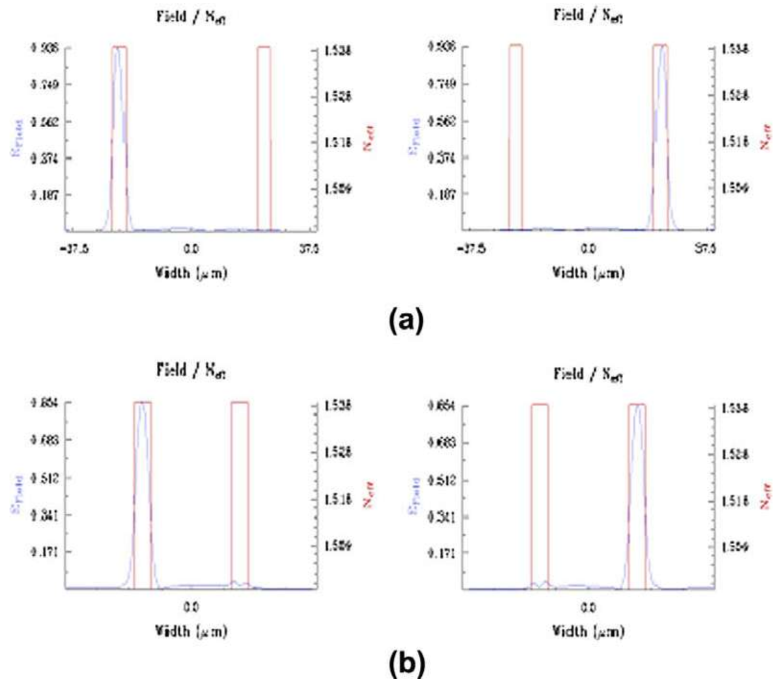

Fig. 2. 2D-BPM analysis of 2 × 2 cross coupler based on: (a) general interference, (b) paired interference.

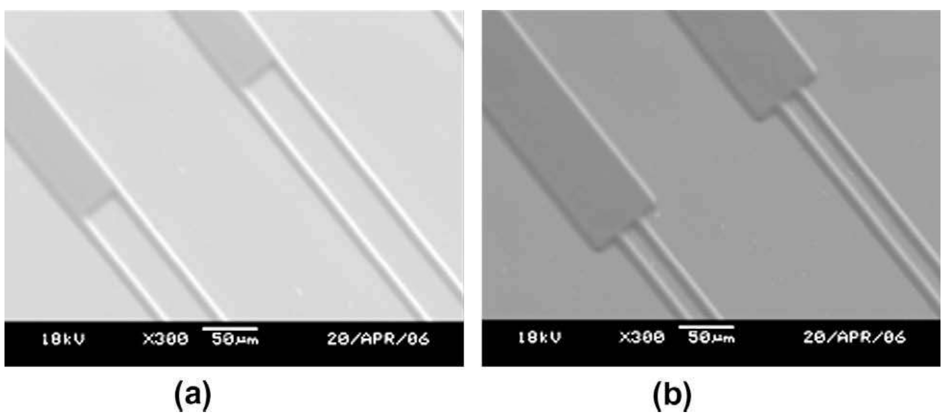

Fig. 3. SEM images of fabricated 2 × 2 cross couplers: (a) general interference (b) paired interference.

measured using a Germanium (Ge) photodetector and the near field profile is imaged onto an infrared camera integrated with beam analyzer software.

The images of the output beams for the fabricated cross couplers are shown in Fig. 4, which indicate good light confinement at the output ports. The average measured crosstalk for 2 × 2 cross coupler (general interference) is found to be −23.52 dB, and −17.81 dB for paired interference type. Meanwhile, the insertion losses have been recorded to give an average value of 3.37 dB for general interference coupler and 2.55 dB for paired interference type.

To justify the performance of our developed cross couplers, comparisons have been made with similar MMI devices, reported in the literature. Wang et al. [13] reported a 2 × 2 cross coupler based on paired interference mechanism in ZPU series polymer, utilizing an RIE development technique. At 1550 nm, they measured a crosstalk of −20 dB and an insertion loss of 0.9 dB. Spiekman et al. [14], using InGaAsP/InP and RIE technique, demonstrated an insertion loss of 2.0 dB and a crosstalk of −28 dB at 1507 nm wavelength for 2 × 2 paired interference coupler. Similarly, work by Nagai et al. [15] on InGaAsP/InP at 1550 nm exhibited a crosstalk of −17 dB for 2 × 2 general interference coupler. Finally, Zinke et al. [16] used silicon on insulator to fabricate a 2 × 2 paired interference coupler with an insertion loss of 1.0 dB and a crosstalk of −17 dB at 1310 nm. These comparisons show that the developed couplers in this work are competitive in terms of crosstalk level but significant drawback in insertion loss. Yet, it proved to us that it is possible to apply a photosensitive BCB 4024-40 polymer in the low-cost development of passive integrated optics components and undoubtedly, the necessary qualities for applications in optical interconnections are still conserved.

6. Conclusion

We have shown that BCB 4024-40 polymer is a low-cost material suitable for fabricating passive optical devices. We have demonstrated 2 × 2 cross couplers based on general interference and

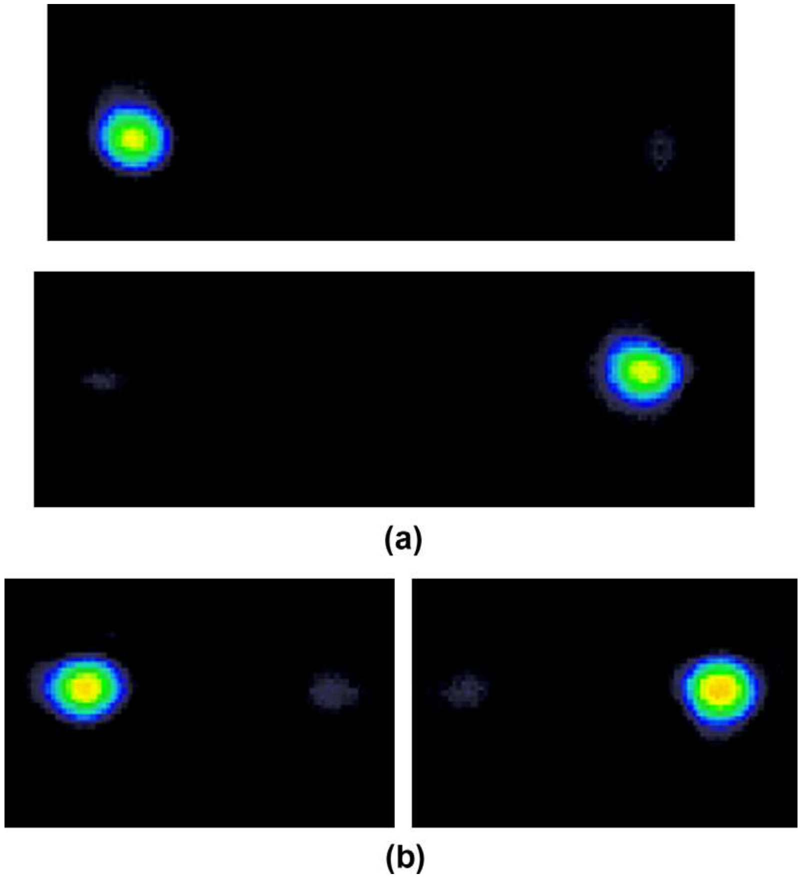

Fig. 4. Near field profile of 2×2 cross couplers: (a) general interference (b) paired interference.

paired interference scheme of MMI technique on BK7 glass using only wet-chemical etching and standard photolithography. At 1550 nm optical wavelength, the average measured crosstalk is about -23.52 dB for the 2×2 general interference couplers, and -17.81 dB for the paired interference couplers, in good agreement with design. Comparison with other MMI-based cross couplers indicates that our BCB 4024-40 polymer based MMI cross coupler is competitive in terms of crosstalk and insertion loss.

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