



Realization of Polarization-Insensitive Optical Polymer Waveguide Devices

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Abstract – We review our studies on the realization of polarization-insensitive optical polymer waveguide devices based on the approach of using thermal control to balance the geometric and stress birefringence in the waveguides. We demonstrate the idea with ridge/rib waveguides, Bragg gratings, directional couplers, and long-period gratings. Polarization-dependent loss compensation is also highlighted.

Index Terms – Integrated optics, optical waveguides, polarization dependence, polymer waveguides, waveguide gratings.

I. INTRODUCTION

Optical polymer waveguides have received increasing popularity in recent years because of the many desirable physical properties that optical polymers can offer in terms of forming inexpensive and robust optical devices (see, for example, [1-3]). A fundamental issue in the design of waveguide-based devices, especially polymer waveguide devices, is the issue of polarization dependence. Because the thermal expansion coefficients of the polymer and the waveguide substrate usually differ greatly, significant stress can be produced in the polymer films and thus complicate the design of polarization-insensitive devices. In practice, it is difficult to characterize the stress-induced birefringence in a polymer waveguide accurately enough to ensure a design for the provision of polarization-insensitive operation. Complications arise as the stress effects depend not only on the materials but also on the waveguide geometry. While it is possible to measure the stress-induced

birefringence in a polymer film with some confidence, the result is not necessarily transferable to a channel structure that results from etching the same film, where stress relaxation is present. A detailed stress analysis [4] is certainly helpful for the understanding of how the stress is modified as the polymer films are shaped.

There are two approaches to tackling the polarization-dependence problem. The first approach is based on using a stress-free polymer waveguide structure, which involves carefully etched shapes to eliminate geometric birefringence and buffer layers to isolate the guiding region from the stress region [5]. The second approach, which we propose recently, is based on thermal tuning to balance the geometric birefringence and the stress birefringence in a polymer waveguide [6-8]. This approach is simpler because it does not rely on a complicated waveguide structure. Besides, the large thermo-optic coefficient of polymer allows effective tuning with a control of only a small range of temperature. In this paper, we present several polymer waveguide devices to demonstrate the idea of thermal tuning for the achievement of polarization-insensitive operation. We also discuss the issue of polarization-dependent loss (PDL) compensation.

II. WAVEGUIDE FABRICATION

The waveguides used in our studies were fabricated with benzocyclobutene (BCB) [9] and various brands of epoxy. However, our methodology and conclusion should be

applicable to general optical polymers.

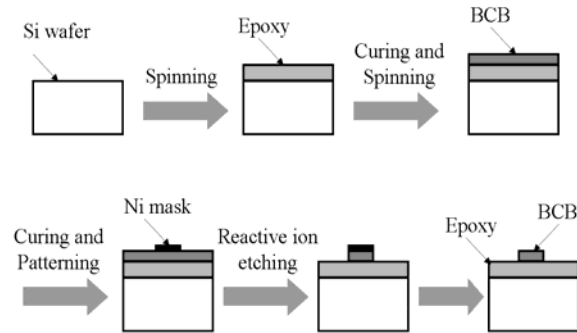


Fig. 1. Procedures for the fabrication of a BCB ridge waveguide.

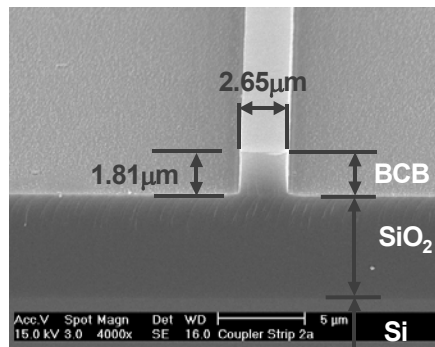


Fig. 2. SEM image of a typical BCB ridge waveguide.

Figure 1 summarizes the procedures for the fabrication of a BCB ridge waveguide on an epoxy substrate by photolithography and reactive-ion etching (RIE) [6]. All the waveguides used in our study were fabricated on silicon wafers, which might be coated with thin silica layers. The BCB film was coated either on an epoxy film as shown in Fig. 1 or directly on a silica-on-silicon wafer. An SEM image of a typical BCB ridge waveguide is shown in Fig. 2. When the BCB film was etched partially, a rib waveguide was obtained [7]. When the BCB core was coated with another layer of epoxy, an embedded channel waveguide was formed [8]. The propagation losses of the waveguides were typically 1 – 2 dB/cm at the wavelength 1.55 μm, depending on the waveguide structure and the epoxy employed. Different epoxy materials were used at different stages of our studies. We used

the more common UV 13 and UV 15 in early years and switched to OPTOCAST 3505 and 3507 lately for achieving better film uniformity.

III. ZERO-BIREFRINGENCE WAVEGUIDES

Zero-birefringence waveguides are the building blocks of many polarization-insensitive devices, such as Bragg gratings, arrayed-waveguide gratings, and unbalanced interferometers. In general it is difficult to fabricate zero-birefringence waveguides because of the precise requirements in the waveguide dimensions [10,11].

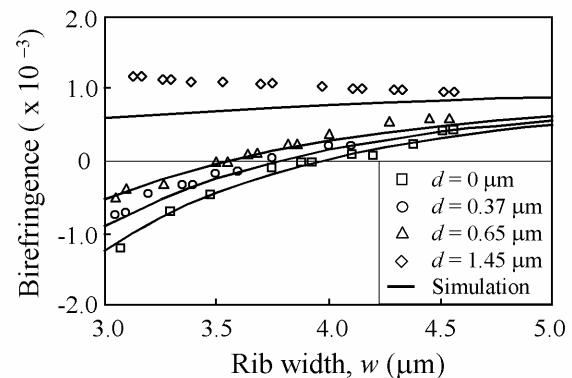


Fig. 3. Dependence of the modal birefringence on the rib width w for different outer slab thicknesses d : experiment (points); simulation (solid curves).

Figure 3 shows the dependence of the modal birefringence on the width w of the rib for a number of rib waveguides on epoxy (UV 15) substrates, where d is the thickness of the outside slabs on both sides of the core (with $d = 0$ for a ridge waveguide) [7]. As the stress distributions in the rib waveguides were not known, the simulation results in Fig. 3, which were calculated by the spectral index method [11], took into account only the stress in the epoxy substrate and assumed complete stress relaxation in the core, and therefore agreed to a less extent with the experimental results for less deeply etched cores (larger values of d) [7]. Nevertheless, the existence of zero-crossing points on the curves shown in Fig. 3 suggests the possibility of designing zero-birefringence polymer rib waveguides, regardless of the presence of stress.

Figure 4 shows how the measured birefringence varies with the temperature. Low birefringence over a wide temperature range was seen with some of the waveguides. In fact, zero birefringence was observed at a specific temperature for one particular waveguide sample ($d = 0.65 \mu\text{m}$ and $w = 3.50 \mu\text{m}$). Our results confirm the feasibility of thermal tuning for maintaining low or even zero birefringence.

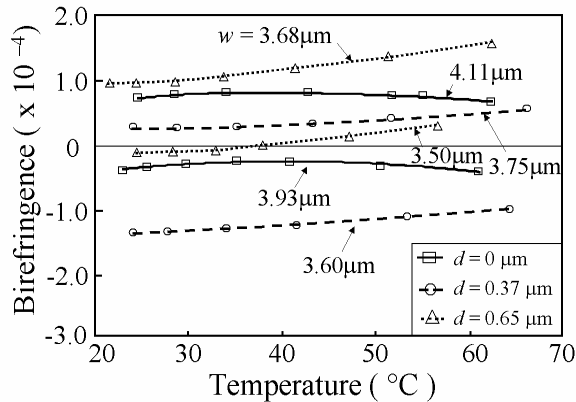


Fig. 4. Temperature dependence of the modal birefringence measured for a number of ridge/rib waveguides.

IV. WAVEGUIDE BRAGG GRATINGS

Being narrow-band filters, Bragg gratings find important applications in wavelength-division-multiplexed systems. While Bragg gratings formed in polymer waveguides can provide good wavelength tunability, polarization dependence is a main issue. We fabricated a number of corrugated Bragg gratings in fully embedded channel waveguides with BCB cores and epoxy (OPTOCAST 3507) claddings [8]. The gratings were introduced in the BCB cores by UV ablation. They had a pitch of $0.515 \mu\text{m}$, a corrugation depth of $\sim 200 \text{ nm}$, and a length of 3 mm . We measured the Bragg wavelengths of the gratings for both polarizations and made comparison with the measurements of the modal birefringence in the waveguides. The results are presented in Fig. 5. As the refractive index of the BCB core could not be measured, in our simulation, we simply assumed a stress-free BCB core and considered only the stress-induced birefringence in the substrate, which could be estimated from

measurements with slab waveguides. As shown in Fig. 5, the simulation results agree well with the experimental results.

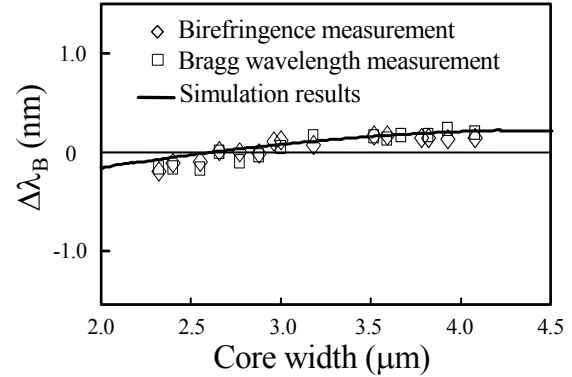


Fig. 5. Dependence of the Bragg wavelength difference between the two polarizations on the core width of a BCB/epoxy embedded channel waveguide.

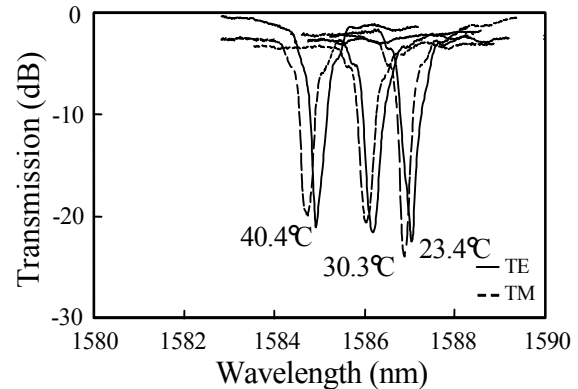


Fig. 6. Normalized transmission spectra measured at different temperatures for the Bragg grating with a core width of $3.07 \mu\text{m}$.

The transmission spectra for a waveguide with a core width of $3.07 \mu\text{m}$ are shown in Fig. 6. Although the Bragg wavelength was not quite polarization independent, the TE and TM transmission spectra crossed each other over the temperature range shown in the figure. The crossing wavelength could be considered as polarization insensitive. The temperature sensitivity of these wavelengths was $-0.14 \text{ nm}/^\circ\text{C}$, which is an order of magnitude larger than the value achieved with a fiber Bragg grating or a Bragg grating fabricated on a silica waveguide.

V. DIRECTIONAL COUPLERS

Directional couplers in the form of two parallel waveguides are the building blocks of many signal distribution devices. By designing the waveguide geometry properly, the splitting ratio of a directional coupler can be made polarization insensitive [12]. We followed the theoretical results and fabricated a number of directional couplers using an embedded waveguide structure with a BCB core and an epoxy (OPTOCAST 3507) upper cladding [13]. The schematic diagrams of the coupler and the waveguide structure are shown in Fig. 7. The couplers had core widths varying from 2.25 μm to 3.45 μm and were fabricated on the same silica-on-silicon substrate. The core separation was fixed at 2.25 μm . The length of the parallel section was set at 156 μm for the core width 2.25 μm and increased at a step of 7 μm for every 0.1- μm increase in the core width. A top-view image of a fabricated coupler is shown in Fig. 8.

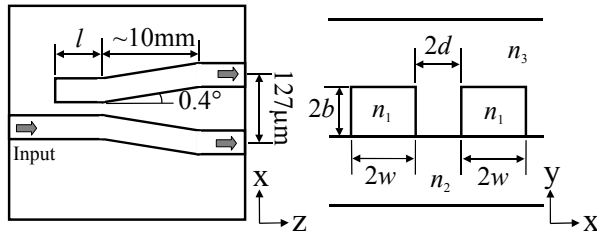


Fig. 7. Top view and cross-sectional view of a waveguide directional coupler.

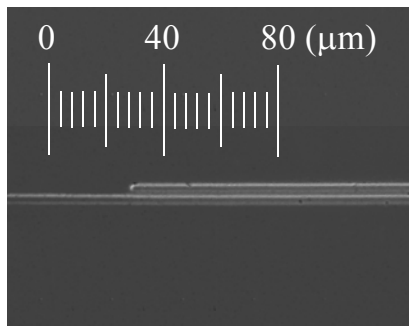


Fig. 8. Top-view image of a fabricated unclad directional coupler.

The splitting ratios of the couplers for the TE and TM polarizations, S_{TE} and S_{TM} , and their ratio, S_r , are shown in Fig. 9 for different core widths. The simulation took into account the stress-induced birefringence in both the BCB cores and the epoxy upper cladding based on the measurements with slab waveguides formed by the same materials. The agreement between the experiment and the simulation is good. As shown in Fig. 9, these couplers show only weak polarization dependence. The splitting ratios of the couplers were also measured at different temperatures. The results for the coupler with a core width of 3.05 μm are shown in Fig. 10. The splitting ratios and the factor S_r vary linearly with the temperature. At $\sim 48^\circ\text{C}$, the coupler can actually operate with a polarization-insensitive splitting ratio. Our results confirm that polarization-insensitive operation can be maintained by controlling the temperature of the coupler.

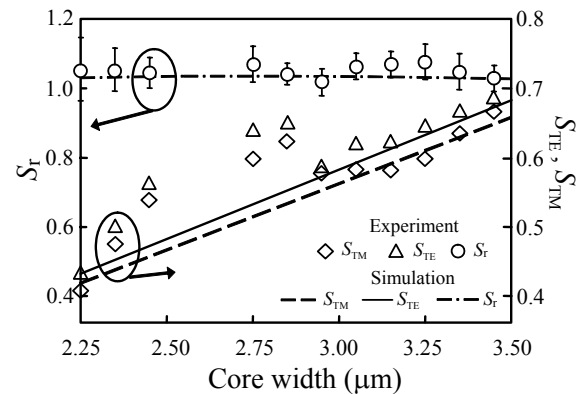


Fig. 9. Dependence of the power splitting ratios on the core width of the directional coupler.

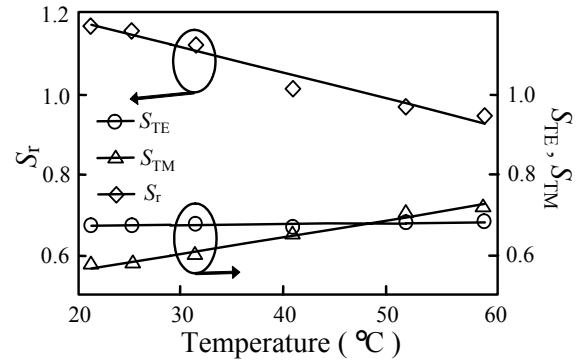


Fig. 10. Temperature dependence of the splitting ratios of the directional coupler with a core width of 3.05 μm .

VI. LONG-PERIOD WAVEGUIDE GRATINGS

Long-period waveguide gratings (LPWGs), namely, long-period gratings formed in planar waveguides [14,15], were proposed recently to relax the geometry and material constraints of the well-known long-period fiber gratings (LPFGs). An LPWG has a pitch of typically several tens micrometers and allows effective light coupling between the guided mode and the cladding modes at specific wavelengths (the resonance wavelengths). Therefore, an LPWG is inherently a band-rejection filter. A schematic diagram of an LPWG formed in a channel waveguide is shown in Fig. 11. In the last few years, we fabricated a large number of polymer LPWGs in different waveguide structures, including ion-exchanged waveguides [16], ridge waveguides [17], and channel waveguides [18,19], and studied extensively their transmission characteristics. Compared with LPFG filters, thermal-tunable LPWG filters can offer a much wider tuning range and higher tuning sensitivity. Figure 12 shows the transmission spectra of a typical experimental LPWG measured at different temperatures and its thermal tuning characteristics. The resonance wavelength of a typical polymer LPWG can be tuned over the (C+L)-band (from 1520 – 1610 nm) with a temperature control of only 10 – 30 °C. The temperature sensitivity of the resonance wavelength of an LPWG filter can be positive or negative, depending on the waveguide parameters [19].

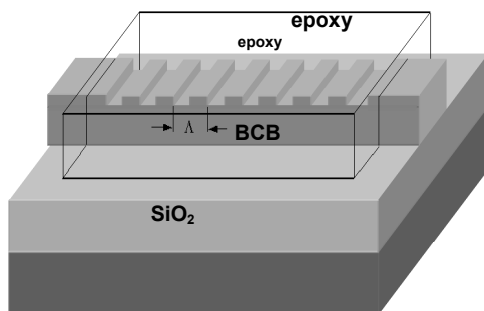


Fig. 11. A corrugated LPWG in a channel waveguide.

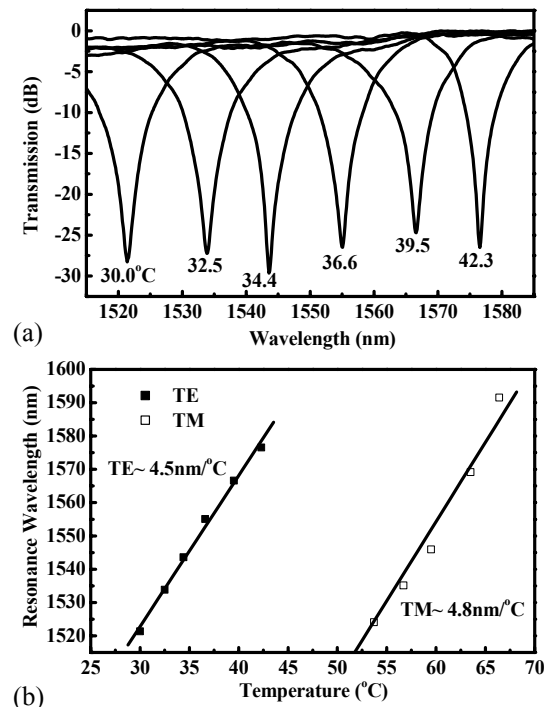


Fig. 12. (a) Transmission spectra (TE polarization) measured at different temperatures for an LPWG formed in a BCB/epoxy channel waveguide and (b) thermal tuning characteristics of the LPWG.

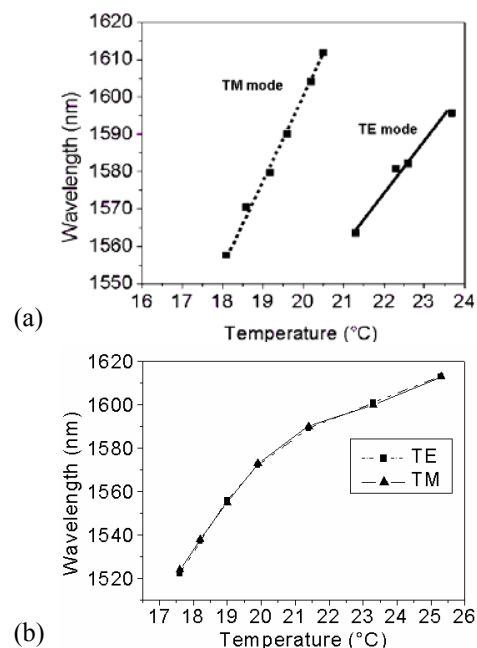


Fig. 13. Dependence of the resonance wavelength of an LPWG fabricated in a BCB channel waveguide (a) before and (b) after the etching of the cladding width.

In general, LPWGs are highly polarization-sensitive devices, as shown by the transmission characteristics in Fig. 12. Nevertheless, a polarization-insensitive LPWG fabricated in a BCB/epoxy channel waveguide was demonstrated by modifying the stress in the waveguide through etching the cladding width of the waveguide [18]. Figure 13 shows the dependence of the resonance wavelength of the LPWG before and after the etching of the cladding width. Note that this particular LPWG exhibits extremely large (positive) temperature sensitivity.

VII. PDL COMPENSATION

PDL is a main concern in the development of polarization-insensitive devices. It is difficult to eliminate PDL completely by perfecting the fabrication techniques, especially for polymer waveguides, where the control of the material properties is less precise. A more practical approach is by using a PDL compensator. It can be seen from Fig. 12 that an LPWG can actually function as an effective PDL compensator. By tuning the rejection bands of the LPWG thermally, a PDL up to 25 dB can be compensated over the range of wavelengths shown in the figure. More recently, we demonstrated a metal LPWG on a polymer channel waveguide [20]. This filter allows electric tuning of the strength and thermal tuning of the resonance wavelength and thus facilitates the implementation of PDL compensation.

VIII. CONCLUSION

We demonstrated a number of polymer waveguide devices, where polarization-insensitive operation was achieved by balancing the geometric and stress effects through thermal control. With thermal control, the precision required in waveguide design and fabrication can be relaxed substantially. As different waveguide structures are required for different polarization-insensitive devices (for example, the conditions for achieving zero birefringence in a rib waveguide are different from those for achieving polarization-insensitive coupling in a directional

coupler), it remains a challenge to demonstrate more sophisticated devices that involve an integration of different types of polarization-insensitive devices.

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