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UV-written long-period waveguide grating coupler for broadband add/drop multiplexing

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ABSTRACT

We demonstrate a UV-written polymer long-period waveguide grating (LPWG) coupler, which offers a bandwidth of ~20 nm, a maximum coupling efficiency of ~80% and ~60% for the TE and TM polarizations, respectively, and a wavelength-tuning range over the (S + C + L)-band (~140 nm) with a temperature control of ~25 °C. The LPWG coupler has the potential to be developed into a practical broadband add/drop multiplexer for coarse wavelength-division-multiplexing applications.

1. Introduction

Optical add/drop multiplexers (OADMs) are critical components in the development of wavelength-division-multiplexed (WDM) transmission networks. A conventional fiber-optic OADM consists of a fiber Bragg grating and two optical circulators [1] and is an expensive and bulky device. Much more compact OADMs with different configurations based on planar optical waveguides have been proposed, which include, for example, Bragg-grating assisted couplers [2,3], Mach–Zehnder interferometers [4,5], arrayed waveguide gratings [6], and X-crossing vertical couplers [7]. All these OADMs can provide a narrow bandwidth to satisfy the channel-spacing requirement (0.4 nm or 0.8 nm) of dense WDM (DWDM) systems. On the other hand, compact broadband OADMs for coarse WDM (CWDM) systems, which require a channel spacing of 20 nm, have not received much attention, regardless of the fact that CWDM systems are widely considered as the desired solutions for short-distance access networks, such as FTTH and LAN applications [8]. In this paper, we demonstrate a compact broadband OADM based on the configuration of two parallel long-period waveguide gratings (LPWGs), which was fabricated with polymer waveguides by using a simple UV-writing technique.

LPWG [9] is the waveguide counterpart of the well-known long-period fiber grating (LPFG) [10]. Such a grating enables strong light coupling from the core mode to selected cladding modes at specific resonance wavelengths and is intrinsically a band-rejection filter. The flexibility of the optical waveguide technology allows a wider range of devices, especially tunable devices, to be realized with LPWGs. In fact, a number of widely tunable LPWG devices, such as band-rejection filters [11], band-pass filters [12], variable attenuators [13,14], and OADMs [15], have been demonstrated experimentally. The LPWG OADM demonstrated [15] consists of two parallel, coupled LPWGs, where light on resonance is coupled from the launching core into the cladding of the composite structure through the grating in the launching core and then coupled into the neighboring core through the other grating [16]. As the optical power transfer between the two cores in such a coupler is achieved purely by the grating effect, the spatial separation between the two cores can be large [16], which can simplify the design work and relax the fabrication tolerance. The first demonstrated OADM of this kind was fabricated by the conventional microfabrication process, where the gratings were etched into the cores of the waveguides. It gave a maximum coupling efficiency up to 34% [15]. The rather low coupling efficiency was due to the difficulty in the prediction of the corrugation depth required and the geometric asymmetry in the fabricated device. In the conventional microfabrication process, the cladding of the composite structure is applied after the gratings have been formed, which means that the grating pitch can only be predicted from the assumed cladding characteristics. On the other hand, the LPWG coupler presented in this paper was fabricated by a simple UV-writing technique [17], which allows the grating to be formed after the waveguide has been fabricated and characterized and, therefore, can provide a more accurate control of the grating

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characteristics. In addition, we employ a UV-insensitive epoxy as the cladding material [17], which makes possible the writing of the gratings into the cores of the coupler. The UV-written coupler offers a bandwidth of ~20 nm and a wavelength-tuning range of ~140 nm with a maximum coupling efficiency as high as ~80% and ~60% for the TE and TM polarizations, respectively.

2. Device fabrication

Fig. 1a shows a schematic diagram of our LPWG coupler, which consists of two parallel gratings LPWG-1 and LPWG-2. The gratings are formed in two well separated cores made of benzocyclobutene (BCB) and embedded in a common epoxy cladding. Light launched into one of the cores is coupled to the cladding mode of the entire structure by the grating in the launching core. Simultaneously, the cladding mode is coupled into the parallel core by the other grating. The output spectra from the two cores show complementary band-rejection and band-pass characteristics. Evanescent-field coupling between the two cores is negligible because of the large core separation [16].

To fabricate the coupler shown in Fig. 1a, we first formed a layer of 1.9-μm thick BCB (Dow Chemical Co.) on a SiO_2–Si substrate (the SiO_2 layer was 3 μm thick) by spin-coating and thermal curing. We then patterned and etched the BCB film into two identical 3-μm wide cores with a separation of 20.5 μm by photolithography and reactive ion etching (RIE). Finally, we spin-coated a 10.7-μm thick epoxy (OPTOCAST 3505 from Electronic Materials Inc.) film on the whole waveguide structure and etched it into a cladding with a nominal width of 45 μm by photolithography and RIE again. The refractive indexes of the BCB and epoxy films for the TE polarization, measured by a prism-coupler system (Metricon 2010) at 1536 nm, were 1.5397 and 1.5085, respectively. The dimensions of the waveguide structure were determined by a surface profiler (Ambios XP-2). An SEM image of the cross-section of a fabricated waveguide is shown in Fig. 1b. We can see from Fig. 1b that the structure is not perfectly symmetrical. The distances from the cladding walls to the left and right cores are 9.2 and 9.8 μm, respectively. The small offset (0.6 μm) was caused by the alignment tolerance and/or the error in the mask aligner during the alignment of the cores with the cladding, which was limited by the facilities available in our laboratory.

The photosensitivity characteristics of BCB and epoxy OPOCAST 3505 in thin-film form have been investigated using a UV lamp (Novacure 2100) as the irradiation source [17]. It has been shown that the refractive index of a BCB film can be increased irreversibly by as much as ~0.01 after a long exposure to the radiation of the UV lamp, while the refractive index of an epoxy film remains unchanged. Therefore, to form the gratings directly in the cores, it is only necessary to expose the composite waveguide structure to the radiation from the UV lamp through a suitable amplitude grating mask over a period of time. In our experiments, the output power density of the UV lamp was set at 2000 mW/cm^2 and the total exposure time was 28 min. The amplitude mask used was a chromium mask, which contained a grating pattern that was 10 mm long and had a pitch of 103 μm. It should be mentioned that the resonance wavelength of the gratings shifted to the longer wavelength during the writing process (because of UV-induced index change in the cores). The grating pitch chosen already took that into account and was expected to produce resonance wavelengths at ~1500 nm for both polarizations. In general, the resonance wavelength of a polymer LPWG can be tuned thermally over a wide range [11,12,14,15]. Therefore, the accuracy in the determination of the grating pitch needs not be too high.

3. Experiment results and discussion

We measured the transmission spectra of the UV-written LPWG coupler with a broadband source and an optical spectrum analyzer. We placed a heat pump below the substrate to control the temperature of the device. Fig. 2a and b show the normalized transmission spectra measured at 39.4 °C for the TE and TM polarizations, respec-

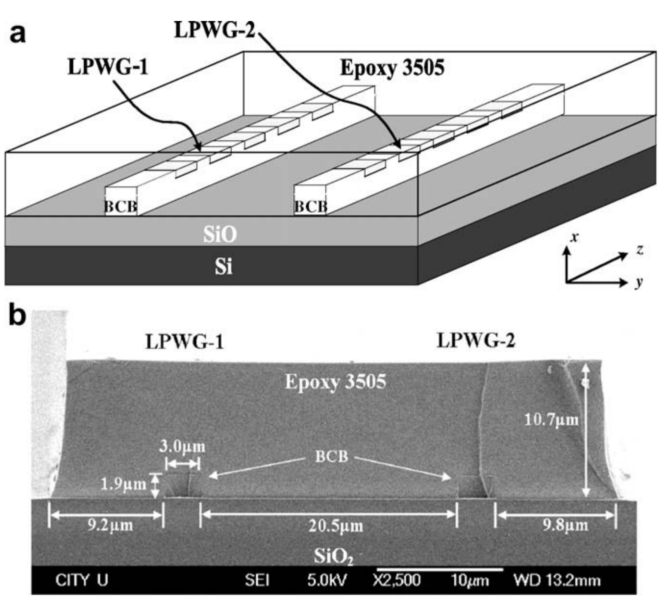

Fig. 1. (a) The LPWG coupler consists of two parallel gratings (LPWG-1 and LPWG-2) formed in the BCB cores embedded in a common epoxy cladding. (b) SEM image of the cross-section of the fabricated LPWG coupler.

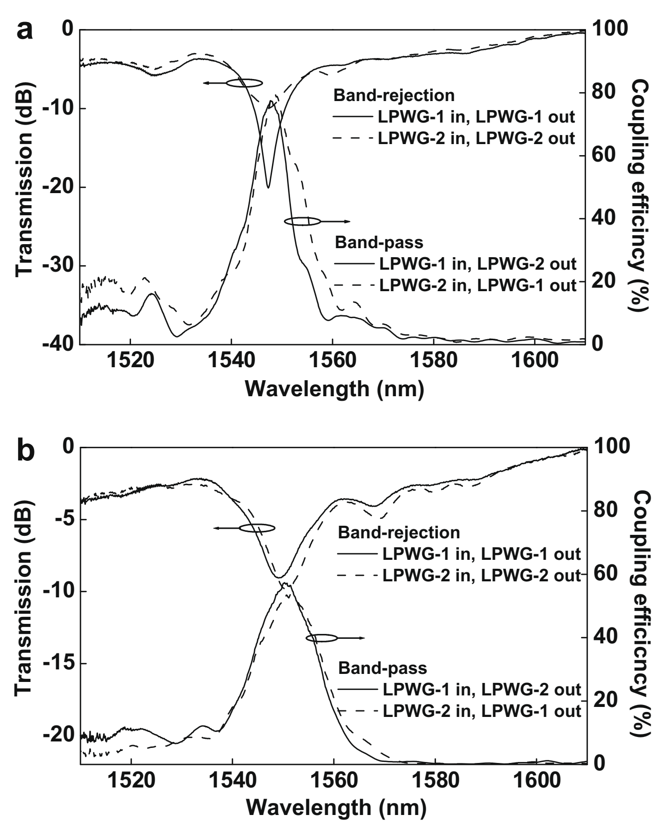

Fig. 2. Normalized transmission characteristics of the LPWG coupler measured at 39.4 °C for (a) the TE polarization and (b) the TM polarization.

tively. Both the band-rejection and band-pass characteristics are shown in the figure. The band-pass spectra are normalized with the light outputs from the two cores obtained before grating inscription. The output from the grating where light was launched into ("LPWG-1 in, LPWG-1 out" or "LPWG-2 in, LPWG-2 out" in the figure) shows band-rejection characteristics. As shown in Fig. 2a, the resonance wavelength at 39.4 °C for the TE polarization is 1547 nm, regardless of which grating light was launched into. The contrasts of the rejection bands for LPWG-1 and LPWG-2 are ~20 dB and ~10 dB, respectively. The difference in their contrasts is mainly due to the slight asymmetry of the waveguide structure, as shown in Fig. 1b. When light was launched into LPWG-1 and detected from LPWG-2 ("LPWG-1 in, LPWG-2 out"), we obtained a passband with a peak coupling efficiency of ~80% (at the resonance wavelength 1547 nm). We obtained practically the same coupling efficiency, when light was launched into LPWG-2 and detected from LPWG-1 ("LPWG-2 in, LPWG-1 out"). It has been proved that the coupling efficiency measured from either grating should always be the same, regardless of the difference in the band-rejection characteristics of the two gratings [15]. The results for the TM polarization shown in Fig. 2b are similar to those for the TE polarization, except that the peak coupling efficiency for the TM polarization is ~60%. The coupling efficiency of the present UV-written LPWG coupler is significantly higher than that reported previously (~34%) using corrugated gratings [15]. The improvement can be attributed to the better geometric symmetry of the present coupler. In the present coupler, the difference between the distances from the cladding walls to the two cores is only 0.6 μm, as shown in Fig. 1b, whereas in the previously reported coupler, the difference is 2.0 μm [15]. A more symmetrical structure gives rise to more balanced gratings (i.e., gratings that have closer resonance wavelengths and strengths), and hence, more efficient coupling between them. As shown by the results in Fig. 2, the coupler functions as a broadband OADM with a bandwidth of ~20 nm.

Using a tunable laser as the light source, we captured the output near-field pattern of the UV-written coupler with a charge-coupled device (CCD) camera. Fig. 3a shows the situation of launching light into LPWG-1 for the TE polarization. At the wavelength 1590 nm, which was far away from the resonance wavelength, we observed no light coupling between the two cores. At the resonance wavelength 1547 nm, however, we observed strong light coupling from the input core to the other core. At 1547 nm, almost 100% of the input light in LPWG-1 was coupled out of the core (LPWG-1 had a 20-dB contrast at 1547 nm), of which ~80% was coupled back into LPWG-2 as the output. Fig. 3b shows the situation of launching light into LPWG-2. At 1547 nm, ~90% of the input light in LPWG-2 was coupled out of the core (LPWG-2 had a 10-dB contrast at 1547 nm) and a total of ~80% of light was coupled to LPWG-1. The results shown in Fig. 3 are consistent with those shown in Fig. 2.

Fig. 4a and b show the normalized transmission spectra for both the TE and TM polarizations measured at three different temperatures, when light was launched into LPWG-1. As shown in Fig. 4, the resonance wavelengths and the contrasts/coupling efficiencies are temperature dependent. At 33.7 °C, the resonance wavelength of the TM polarization is shorter than that of the TE polarization, while at 39.4 °C, it is the other way round, which suggests the existence of a temperature at which the resonance wavelengths of the two polarizations are equal. As shown in Fig. 4, the resonance wavelengths of both polarizations are the same at 37.0 °C. The presence of a polarization-independent resonance wavelength has also been observed with a single LPWG fabricated on a polymer ridge waveguide [18].

Fig. 5 summarizes the temperature dependence of the resonance wavelength and the coupling efficiency of the coupler for both polarizations. As shown in Fig. 5a, the temperature sensitivities of the resonance wavelengths of LPWG-1 and LPWG-2 are practically the same. The values for the TE and TM polarizations are 4.3 and 5.5 nm/°C, respectively. With a temperature control of ~25 °C, we can tune the resonance wavelength almost linearly over a range of ~140 nm, which covers the entire (S + C + L)-band. As shown in Fig. 5b, the coupling efficiency of the coupler for the TE polarization varies between ~45% and ~80% over the temperature range shown in the figure with the maximum value ~80% occur-

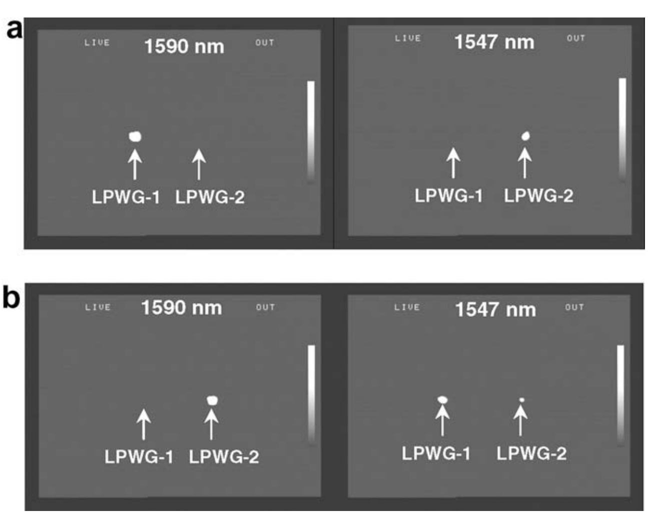

Fig. 3. Output near-field images taken by a CCD camera for the TE polarization at 39.4 °C when light was launched into (a) LPWG-1 and (b) LPWG-2. The arrows indicate the locations of the cores.

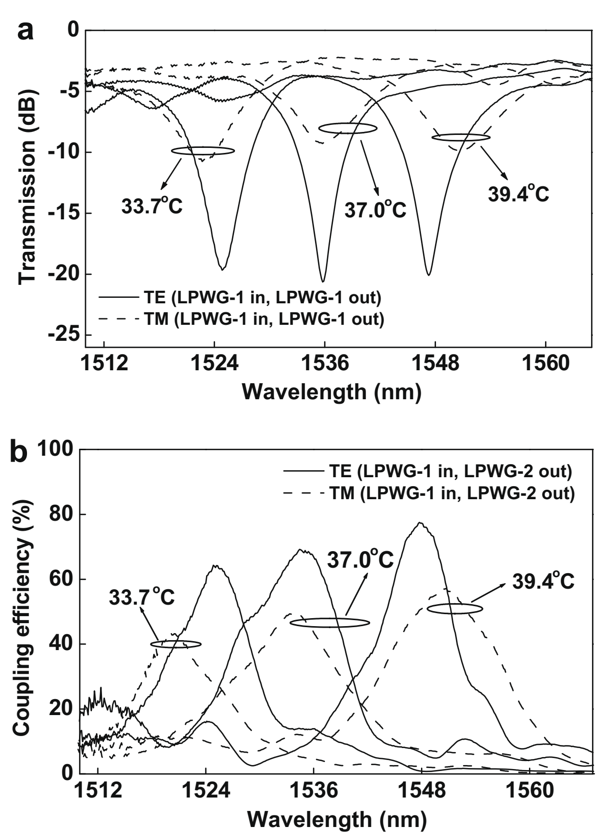

Fig. 4. Normalized transmission characteristics of the LPWG coupler measured from (a) the launching core (LPWG-1) and (b) the coupled core (LPWG-2) for the TE and TM polarizations at three different temperatures.

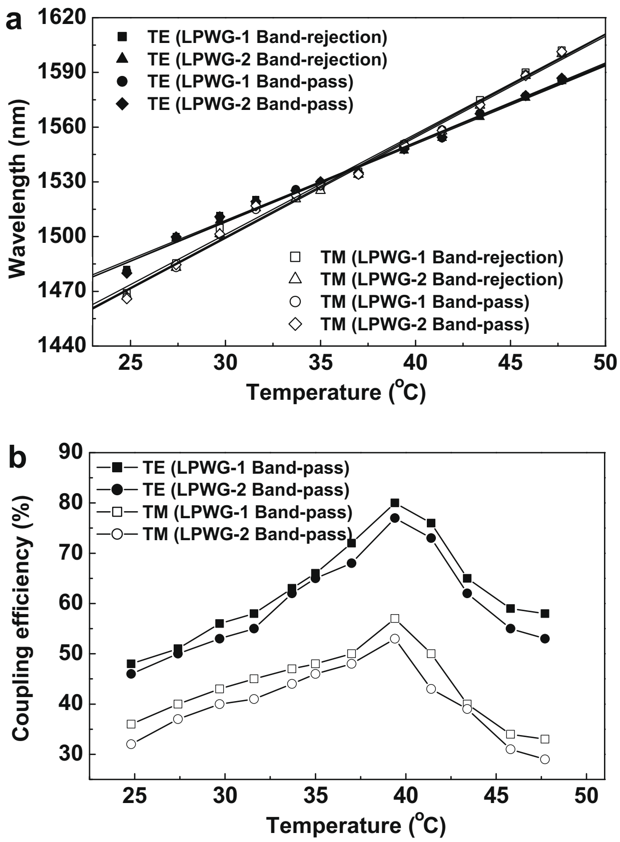

Fig. 5. Temperature dependences of (a) the resonance wavelengths measured from the band-rejection and band-pass outputs of the coupler and (b) the coupling efficiencies.

ring at 39.4 °C, where the resonance wavelength is 1547 nm. For the TM polarization, the coupling efficiency varies between ~30% and ~60% with the maximum value ~60% occurring at 39.4 °C, where the resonance wavelength is 1550 nm. The variation of the coupling efficiency with the temperature can be attributed to the thermo-optically induced changes in the refractive indexes of the materials and hence the mode-field distributions. The fact that the TE and TM polarizations show different characteristics is the result of the symmetry property of the waveguide structure. Because of the large bandwidth (~20 nm), thermal stability is not a problem, regardless of the large temperature sensitivity of the resonance wavelength. On the other hand, the large thermal tuning capability of the device could be explored as a means of achieving reconfigurable add/drop multiplexing.

Finally, we should mention that, while the polymer materials employed in our study are good enough to demonstrate the idea, they are not necessarily the most suitable materials for practical devices. The advancement in polymer materials for integrated optics applications and the practical issues on the packaging of polymer waveguide devices have been discussed in detail elsewhere (see, for example, Refs. [19] and [20]).

4. Conclusion

We demonstrated a UV-written polymer LPWG coupler, which offered a bandwidth of ~20 nm, a maximum coupling efficiency of ~80% and ~60% for the TE and TM polarizations, respectively, and a wavelength-tuning range of ~140 nm across the entire (S + C + L)-band with a temperature control of only ~25 °C. We also observed the existence of a polarization-independent resonance wavelength at a specific temperature. By improving the geometric symmetry of the waveguide structure and employing a UV-writing process to form the grating, we achieved significantly better results, compared with the proof-of-principle experiment reported recently [15]. However, more research effort is needed to further improve the coupling efficiency and the spectral characteristics for such a coupler to be useful as a practical broadband OADM in CWDM systems.

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