InGaAsP Thin-Film Microdisk Resonators Fabricated by Polymer Wafer Bonding for Wavelength Add–Drop Filters

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***Abstract*—10-μm-diameter InGaAsP thin-film microdisk resonators have been fabricated using polymer-wafer bonding with benzocyclobutene. This wafer bonding process is to provide strong two-dimensional mode confinement in the waveguide and reduce the optical propagation loss. The measured resonance linewidth at wavelength 1.55 μm is about 0.22 nm with a free-spectral range of 20 nm. The narrow linewidth and large free-spectral range make these devices conducive to the applications in dense wavelength division multiplexed systems.**

***Index Terms*—Benzocyclobutene, InGaAsP, microdisk, polymer wafer bonding, wavelength add–drop filters.**

I. Introduction

WAVELENGTH add–drop filter is one of the essential components in current dense wavelength-division-multiplexed (DWDM) systems [1]. Microdisk or microring resonators with narrow linewidth and large free-spectral range (FSR) have the potentials of functioning as wavelength add–drop filters [2]–[5]. Recently, waveguide-coupled microdisk and microring resonators with small sizes (diameter ~ 10 μm) fabricated by deep dry etching have been demonstrated to have narrow resonance linewidths (~ 0.18 nm) and large FSRs ($\sim$21.6 nm) in AlGaAs–GaAs material system [3], [5]. However, to our best knowledge, there has not been much work reported on InGaAsP–InP-based microdisk or microring resonators.

In this letter, we report for the first time the fabrication and experimental results of InGaAsP thin-film microdisk resonators fabricated involving benzocyclobutene (BCB) polymer-wafer bonding. The polymer-wafer bonding process enables us to bond a submicron InGaAsP epitaxial layer onto a transfer substrate with BCB polymer as the intermediate medium. There are a few advantages associated with this bonding technique. First, strong mode confinement can be achieved not only in the lateral direction, but also in the vertical direction (direction perpendicular to the wafer plane) as BCB has a much lower refractive index ($n \sim 1.53$) than InGaAsP. The strong mode confinement in the vertical direction helps to reduce substrate leakage loss. Second, the refractive index contrast in the lateral direction is changed from about $3.4:1.0$ to $3.4:1.53$, which helps to reduce the sidewall scattering loss. This is because the amount of scattering due to sidewall roughness scales with the contrast between the square of the refractive indices of the waveguide and its surrounding.

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II. Device Fabrication

The geometry of our microdisk resonators with coupling waveguides is the same as that in [5]. The wafer structure with a 0.4-μm-thick InGaAsP ($\lambda_g = 1.2$ μm) guiding layer is grown on an InP substrate by molecular beam epitaxy. To prepare the epitaxy sample for etching, a 400-nm-thick SiO_2 layer was deposited by plasma-enhanced chemical vapor deposition (PECVD). This SiO_2 layer acts as a hard mask for etching. The wafer is then patterned through a soft mask of 180-nm-thick 2% polymethylmethacrylate (PMMA) using electron-beam lithography. The pattern on the PMMA mask was subsequently transferred to the underlying SiO_2 layer using reactive ion etching (RIE). Dry etching utilizing inductively coupled plasma (ICP) with a gas mixture of $Cl_2:Ar^+$ $(2:3)$ was employed to transfer the pattern onto the epitaxy wafer through the SiO_2 hard mask at an elevated temperature of 250 °C. The etching depth was about 1.3 μm. After the etching process, we removed the SiO_2 hard mask using buffered HF.

The above procedure defines a typical deeply etched ridge waveguide structure. In such a structure, there is a strong lateral mode confinement because of the large index contrast ($3.4:1.0$). However, in the vertical direction, the refractive index contrast between the guiding layer and the substrate is relatively small ($3.41:3.17$). As the result, a large part of the guided mode will enter into the substrate, which will cause a lot of scattering losses into the substrate during the propagation and decrease the optical throughput.

To increase mode confinement, we need to increase the refractive index contrast in the vertical direction. We can obtain a large refractive index contrast by using polymer wafer bonding, as polymer usually has a much lower refractive index than semiconductors. In our experiment, we use BCB as the polymer, which has been utilized to fabricate low-loss waveguides and modulators. The details of this bonding process can be found in [6] and [7]. Basically, we first spin BCB on both the patterned sample wafers and the transfer substrates (GaAs in our case). We then flip the sample over and put it directly onto the transfer substrate. We give some pressure or weight to push the two wafers

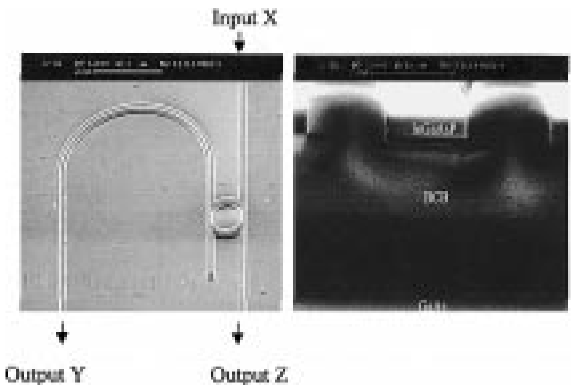

Fig. 1. (a) Scanning electron micrograph of a BCB bonded 10-μm-diameter microdisk resonator with coupling waveguide. (b) Cross section of a BCB bonded waveguide.

together and then put the whole wafer into a nitrogen-filled furnace at 250 °C for one hour. After that, BCB becomes fully cured and the two wafers are very tightly glued together. Finally, the InP substrate was removed using selective wet etching ($HCl : H_3PO_4 = 2 : 3$).

Fig. 1(a) shows the scanning electron microscope (SEM) image of a 10-μm-diameter BCB-bonded microdisk resonator. The straight waveguide is for input coupling and the U-shape waveguide is for output coupling. Light is input into port X and partially coupled into the microdisk resonator and coupled out by the U-shape waveguide through port Y when the wavelength is on resonance. When off resonance, light will pass through the straight waveguide and exit from port Z. We call port Y the transmission port and port Z the reflection port. All the coupling waveguides are tapered from 2 μm down to 0.4 μm near the microdisk resonator. The length of tapered region is 500 μm. The radius of U-shape waveguide is 25 μm. The gap between the coupling waveguide and disk resonator is about 0.18 μm. This gap is filled with BCB polymer after the bonding process, which reduces the lateral refractive index contrast and increases the coupling efficiency. A cross section of the bonded waveguide structure is shown in Fig. 2(b). From Fig. 2(b), we can see that the 0.4-μm-thick InGaAsP guiding layer is surrounded by BCB polymer and air. In this structure, the BCB layer must be thick enough to prevent the guided mode from leaking into the transfer substrate as GaAs has a higher refractive index than BCB. But, it should not be too thick to make the wafer cleaving difficult. In our experiment, the thickness of BCB was chosen to be 3.0 μm. Note that in Fig. 2(b) the BCB layer is higher than the top of the waveguide. This is because the etching depth (1.3 μm) is larger than the waveguide thickness (0.4 μm). In the next section, the transmission and reflection measurement results will be discussed.

III. Results and Discussion

The waveguide coupling was achieved by using end-firing method. The light from a tunable diode laser with a center wavelength of 1550 nm was coupled into the device from port X using a high numeric aperture lens (N.A. $= 0.55$). The output from port Y or port Z was focused by another lens and imaged onto an IR camera and a photodetector. The insertion loss is about 15 dB. A movable pinhole was placed in front of the photodetector to select either output.

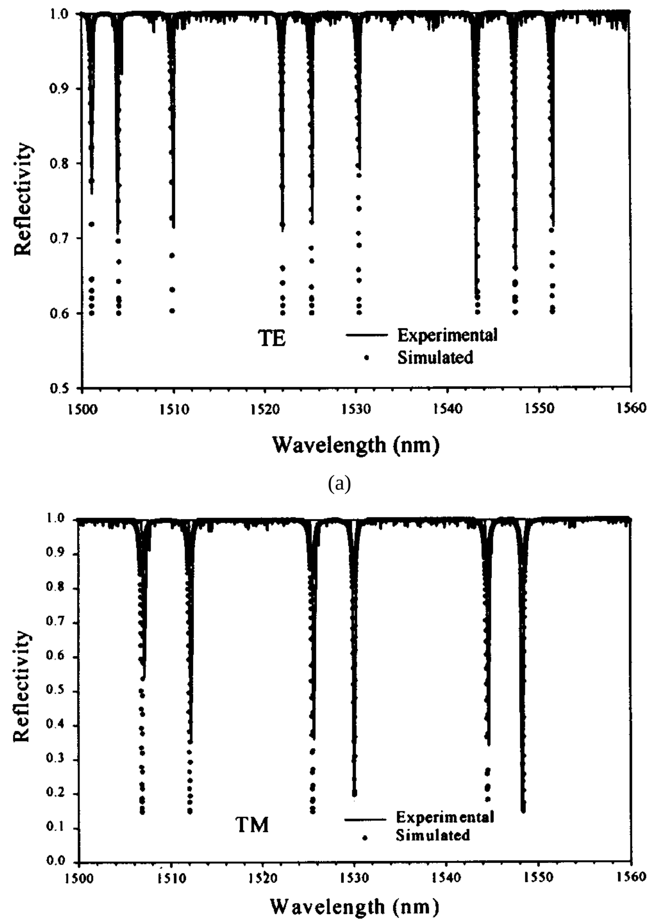

Fig. 2. Reflectivity as the function of wavelenght of a 10-μm-diameter BCB bonded microdisk resonator with coupling waveguide. —Experimental . . . Simulated (a) TE and (b) TM.

The reflection spectra for the TE and TM modes of a 10-μ m-diameter BCB-bonded microdisk resonator are shown in Fig. 2 (The TE polarization is parallel to the substrate). For the TE case, there are three sets of resonance modes. Each set has a FSR $\Delta\lambda_{\text{fsr}} \approx 21$ nm with a full width at half maximum $\delta\lambda_{\text{FWHM}} \approx 0.25$ nm, which results in a finesse of 84. For the TM case, we have 2 sets of resonance modes for which $\Delta\lambda_{\text{fsr}} \approx 20$ nm and $\delta\lambda_{\text{FWHM}} \approx 0.22$ nm, which gives a finesse of 91. Note that the presence of the multiple sets of resonance modes is due to the guiding layer not being single mode waveguide. Therefore, higher order modes could be excited in the disk resonator. The large FSR is due to the small diameter of the disk and the narrow linewidth is due to the low cavity loss. As we know, in microdisk resonators, whispering gallery modes (WGMs) can have high-Q values, where $Q = \lambda/(\delta\lambda_{\text{FWHM}})$. In our case, both the TE and TM resonance modes show Q value as high as 8000.

We calculated the reflectivity r by using the following:

$$r = 1 - \frac{t_{\max}}{1 + F\sin^2\left[2\pi n_{\text{eff}}(\lambda)l/\lambda\right]} \tag{1}$$

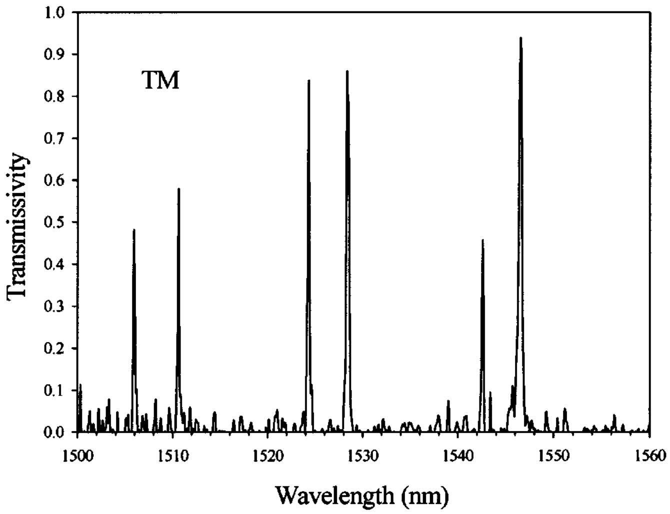

Fig. 3. Measured transmissivity as the function of wavelength of a 10-μm-diameter BCB bonded microdisk resonator for the TM case.

where

- $t_{\max}$ maximum transmissivity and $t_{\max} = (1-R)^2A/(1-RA)^2$;
- F coefficient of finesse given by $F = 4RA/(1-RA)^2$ with $A = \exp(-\alpha l)$;
- R $= 1-\kappa$;
- l $= \pi D_{\text{eff}}/2$;
- D_{eff} collective disk diameter;
- α loss coefficient in the disk resonator;
- κ coupling coefficient between the coupling waveguide and the disk resonator;
- n_{eff} being the propagating effective refractive index.

To fit the experimental data, we first use the conformal transformation and WKB approximation as described in [8] to calculate $n_{\text{eff}}(\lambda)$. We substitute $n_{\text{eff}}(\lambda)$ into (1) to get the reflectivity at each wavelength by assuming $\alpha = 3.6$ cm^{-1}, $\kappa = 0.025$, $D_{\text{eff}} = 10.0$ μm for TE and $\alpha = 1.5$ cm^{-1}, $\kappa = 0.02$, $D_{\text{eff}} = 10.0$ μm for TM. The simulated results are shown in Fig. 2 from which we see that the resonance wavelengths match the experimental data reasonably. Note that the TE modes suffer more losses than the TM modes in our devices. This is probably due to larger scattering loss in the TE mode case. From Fig. 2, the maximum transmissivity is about 40% for TE and 90% for TM. Fig. 3 shows the measured transmissivity from port Y for the TM case. Compared with Fig. 2(b), we can see that $t_{\max} \approx 1 - r_{\min}$ for most of the resonant wavelengths, which means the total loss from disk resonator and coupling waveguide is small. The TE case has similar results. Note that the location of the resonance dip is subjected to digitizing error and the resolution limitation of wavelength scanning (~0.05 nm). We estimate the total loss to be about 0.7 dB for a 10-μm-diameter disk resonator and 1-mm-long tapered coupling waveguide [7]. Based on our experimental results, the devices reported here might function as wavelength add–drop filters. However, the use of single resonator cannot provide flat-topped filtering characteristics which can be achieved with the use of multiple resonators [2].

IV. Conclusion

With polymer-wafer bonding process, we have successfully fabricated 0.4-μm-thick thin-film InGaAsP microdisk resonators with 10-μm-diameter. These resonators display a linewidth as narrow as 0.22 nm and a FSR as large as 21 nm. Further improvements, such as to achieve single mode operation, higher order filtering characteristics and wavelength tuning, will make these devices to be useful as wavelength add–drop filters in DWDM applications.

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