Compact Ring Resonators using Conventional Waveguides, Etched Beam Splitters and Total Internal Reflection Mirrors

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Abstract: Compact single ring resonator bandstop filters with 11.5 nm free spectral range and 12 dB extinction ratio are demonstrated in GaAs/AlGaAs using weakly guided waveguides, etched beam splitters and total internal reflection mirrors.

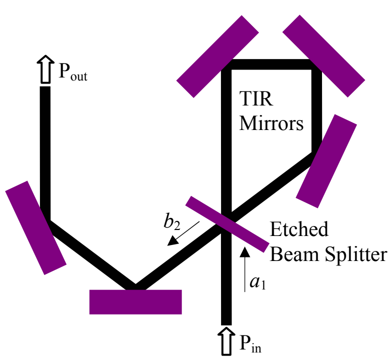
OCIS code: (130.7408) Wavelength filtering device; (220.4610) Optical fabrication

1. Introduction

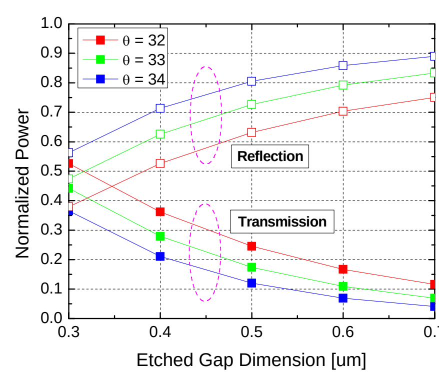
Ring resonators are very attractive components due to their promise of compact size and high functionality, which may enable high levels of photonic integration. Small size, large free-spectral-range (FSR) and high extinction ratio (ER) are among the desired characteristics for WDM application. To achieve high ER, a certain amount of power (20 % – 40 %) should couple from the optical bus to the resonator per pass to meet the critical coupling condition [1]. Large FSR can be obtained by decreasing the resonator circumference for a given material platform and wavelength range. Small resonator circumference also helps to increase integration density. Ring or racetrack shaped resonators require very strongly confining waveguides for reduced size. But such waveguides may not have good optical properties such as low loss and high optical gain. On the other hand it is difficult to reduce the circumference using weakly guiding waveguides with good optical properties due to high bending loss. Total Internal Reflection (TIR) mirror is a promising solution for reducing resonator length using conventional waveguides without high radiation loss, but resonator size could still be rather large due to the relatively long coupler [2]. Recently we proposed compact resonators using an etched beam splitter (EBS) for coupling in and out of the resonator and investigated such EBS and resonators using FDTD simulation [3]. In this paper, we describe the design, fabrication and characterization of bandstop characteristics of ring resonators based on conventional waveguides, EBS and TIR mirrors.

2. Device Description and Simulation

The proposed resonator is formed with one EBS and three TIR mirrors as shown in Fig. 1 (a). In addition, two TIR mirrors outside the resonator are used to direct the output for convenient measurements using cleaved facets. The coupling through the EBS depends on the angle of incidence, the dimensions of the etched gap and the refractive index of material filling the gap [3]. This allows controlling the coupling coefficient of the EBS by changing the etched gap dimension and the angle of incidence without increasing resonator length. Fig. 1 (b) shows the transmission (coupling) and reflection coefficients of a Benzocyclobutane (BCB, n = 1.53)-filled EBS at 1555 nm as a function of etched gap dimension for different angles of incidence using 2-dimensional FDTD calculations.



(a)



(b)

Figure 1. (a) Top schematic of a micro resonator formed using one EBS and three TIR mirrors, and (b) characteristics of BCB-filled EBS as a function of gap dimension for different angles of incidence at 1550 nm using 2D-FDFD calculations.

To choose the appropriate parameters of EBS, band stop filter characteristics are analyzed as a function of round trip resonator loss, power coupling coefficient and coupler loss. The ratio of output and input wave amplitudes can be described as [1]

$$\frac{b_2}{a_1} = \frac{\sqrt{1-\alpha_c - k^2} - (1-\alpha_c)\cdot e^{-(\alpha_T + j\varphi)}}{1-\sqrt{1-\alpha_c - k^2}\, e^{-(\alpha_T + j\varphi)}} \qquad (1)$$

where α_c is coupler loss and k is field coupling coefficient. φ and α_T are the round trip phase change and loss inside the resonator, respectively. The extinction ratio as function of power coupling coefficient for different resonator round trip loss and coupler loss is plotted in Fig. 2. The required power coupling coefficient for critical coupling increases as resonator loss increases, but coupler loss does not affect the extinction ratio much. For example, the required power coupling coefficient is 0.3 ~ 0.45 to obtain an ER larger than 20 dB for 2 dB resonator round trip loss. For two resonators with circumference of 55 μm and 110 μm, an EBS with incident angle of 34° and gap of 0.3 μm is chosen based on this calculation and EBS properties given in Fig. 1 (b).

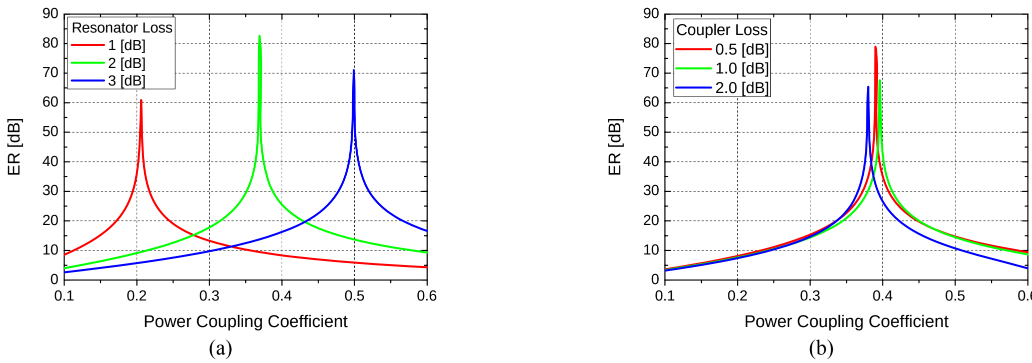
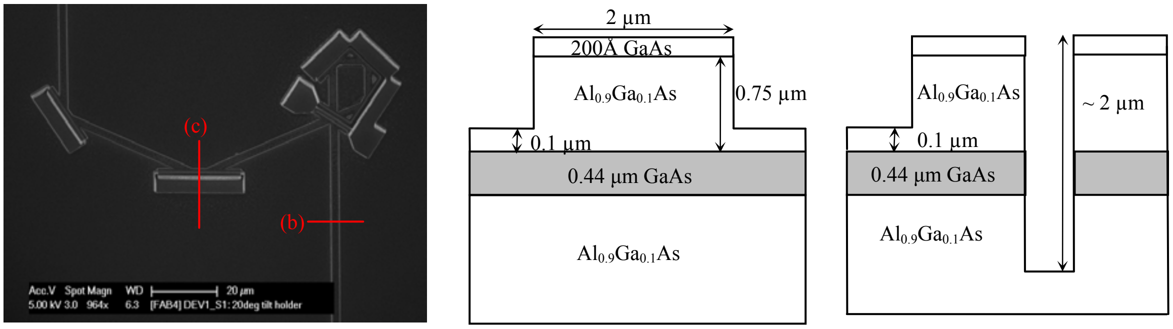


Figure 2. Extinction ratio as function of power coupling coefficient into resonator for (a) different resonator round trip loss with lossless coupler, and (b) different coupler loss with 2 dB resonator round trip loss.

3. Device Fabrication

Calculations indicate that axes of the input output waveguides and the etched facet of the EBS or TIR mirror should be aligned precisely for low loss coupling and reflection. We use a self-aligned process to eliminate alignment between waveguides and etched facets. This helps to reduce the loss at the etched facets. First, all patterns including the waveguides, etched beam splitters (EBS), and TIR mirrors are defined using electron beam lithography. Then, 100Å titanium and 1500Å nickel were evaporated by e-beam evaporator and lifted off to form the etching mask. This mask is used to etch the waveguides and EBS and TIR mirrors in two etching steps. Since entire device is defined by the same mask, the precise alignment between waveguides and mirror facets are guaranteed. Next, the EBS and TIR mirror patterns are covered by photoresist to avoid unnecessary damage to the etch mask during waveguide etching. As shown in Fig. 3 (b), $Al_{0.9}Ga_{0.1}As$ was etched to a depth of 0.65 μm to form the waveguide using the reactive ion etching (RIE) with BCl_3:$SiCl_4$. The etch depth is precisely controlled with laser monitoring to guarantee the single mode operation. After waveguides are etched, 4000 Å SiO_2 film was deposited over the entire sample by plasma enhanced chemical vapor deposition (PECVD) and areas which would be deeply etched were opened using standard photolithography. This exposes the original mask. This is followed by deep-trench etching using inductively coupled plasma (ICP) RIE with BCl_3: Cl_2: Ar. The epitaxial layer is etched to a depth of 2.0 μm, as illustrated in Fig. 3 (c), which is deeper than the mode size. Finally, BCB was spin-coated to fill the deeply-etched area and fully cured. The refractive index of BCB after curing is 1.53 at 1.55 μm. Fig. 3 (a) shows the fabricated device before BCB filling process. To minimize the optical feedback due to facet reflection, the input/output waveguides are gradually tilted to an angle of 7° at the cleaved facet. After cleaving the device, an antireflection coating of Ta_2O_5 is applied to each facet.



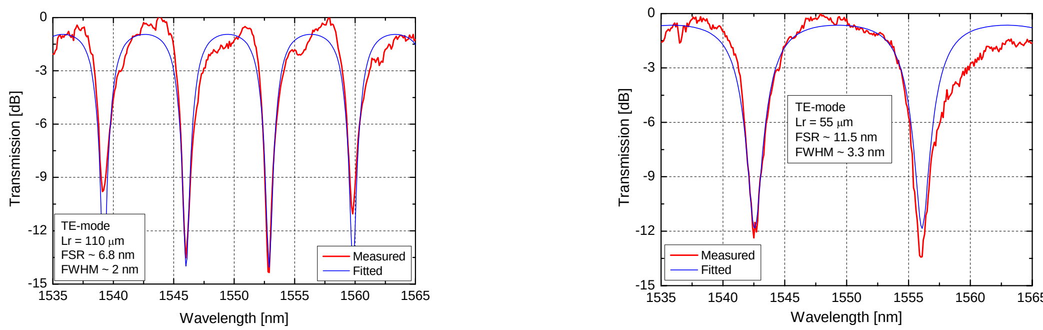
(a) (b) (c)

Figure 3. (a) SEM picture of fabricated device before BCB filling, (b) Waveguide structure along b (c) deeply-etched structure along c.

4. Results

The filter response for TE mode was measured using tunable laser coupled to the input waveguide with a lensed fiber. The output was focused onto a detector using a microscope objective. The measured responses were fitted with the equation (1) to estimate resonator loss and power coupling coefficient. The resonator loss, which is mainly due to 3 TIR mirrors, is estimated as 2.2 dB for both resonators. The power coupling coefficients are 0.48 and 0.45 for resonator with circumference of 55 μm and 110 μm, respectively. These are very close to our design targets. The difference may be due to a change of gap-dimension during fabrication.

As shown in Fig. 4 (a), the FSR, bandwidth and ER for resonator with circumference of 110 μm are 6.8 nm, 2 nm and 13 ~ 14 dB around 1.55 μm, respectively. The resonator with circumference of 55 μm has a FSR of 11.5 nm, bandwidth of 3.3 nm, and ER of 12 dB. Results show some wavelength dependence of ER since EBS was optimized for 1.55 μm.



(a) (b)

Figure 4. Measured and fitted response of bandstop filter with 2 output TIR mirrors: (a) L_R = 110 μm and (b) L_R = 55 μm.

5. Summary

We have demonstrated compact ring resonators using conventional waveguides, BCB-filled etched beam splitter and total internal reflection mirrors. The circumference of resonator based on weakly guided waveguide is reduced to 55 μm, which shows extinction ratio of 12 dB and free-spectral range of 11.5 nm. Such devices may enable high levels of photonic integration.

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