Total Internal Reflection Mirror-Based InGaAsP Ring Resonators Integrated With Optical Amplifiers

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***Abstract*—Novel ring resonators combining very small multimode interference (MMI) couplers, low loss total internal reflection (TIR) mirrors, and a semiconductor optical amplifier in InGaAsP material system are reported for the first time. The MMI length of 113 μm is among the shortest reported. Average TIR mirror loss is about 1.1 dB per mirror. The material platform and fabrication process used are the same used for other active and passive devices except for a deep etch step. Hence, such resonators are easily integrated with other active and passive devices. A free spectral range of approximately 2 nm is observed near 1568 nm along with an on–off ratio of 14 dB, a full-width at half-maximum of about 0.3 nm, a finesse of more than 6, and a Q-factor of more than 4900.**

***Index Terms*—Band stop filter, microring resonator, multimode interference (MMI) coupler, semiconductor optical amplifier (SOA), total internal reflection (TIR) mirror.**

I. Introduction

RING resonators are very attractive components due to their promise of compact size and high levels of integration to yield high functionality. To deliver this promise, several requirements should be met. First of all, a ring of small circumference and low loss should be possible. In ring or disk type geometries main loss is due to radiation which limits the curvature and the size of the ring. In addition to a small resonator circumference, a certain amount of power (20%–40%) should couple from the optical bus to the resonator per pass. Finally, ring resonators should easily be integrated with other devices to realize the promise of high levels of integration yielding high functionality. This requires that the fabrication process and the material platform of the resonator should be the same as that required for other devices.

This letter describes a novel device that achieves all these requirements. Resonators are formed using total internal reflection (TIR) mirrors. Hence, round-trip loss is limited by the mirror loss rather than the radiation loss of the curved waveguides making scaling of the resonators to very small sizes possible. There is also no need to deeply etch the waveguides and regular waveguides can be used. Coupling in and out of such a compact resonator is achieved using very short multimode interference (MMI) couplers [1]. Furthermore, the process and material platform used are the same used for other devices such as lasers and wavelength converters. Therefore, high level of integration with other devices is possible.

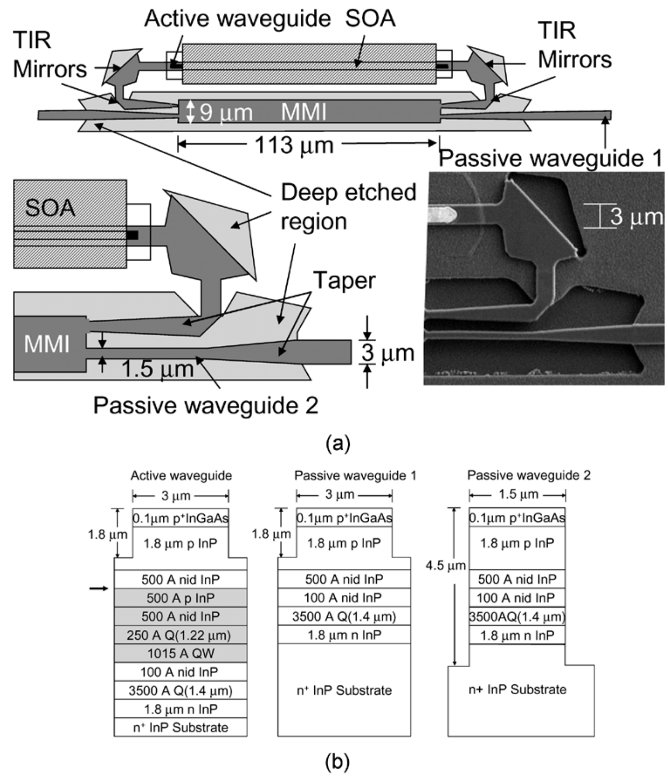

Fig. 1. (a) Top schematic of the resonator and details of the TIR mirrors and tapers. (b) Cross-sectional schematics of the three different types of waveguides used within the resonator.

II. Device Description

Fig. 1(a) and (b) shows the top and various cross-sectional schematics of the resonator integrated with a semiconductor optical amplifier (SOA). The resonator itself consists of four TIR mirrors, an MMI coupler, and an SOA. These parts are connected by three different types of waveguides whose cross sections are shown in Fig. 1(b). The core of all the waveguides is 0.35-μm-thick InGaAsP with bandgap energy corresponding to 1.4 μm. The lower and upper claddings are 1.8-μm-thick n and p InP, respectively, on n+ InP substrate with a 0.1-μm p+ InGaAs cap layer. The passive waveguide 1 is 3 μm wide and is etched 1.8 μm deep. The passive waveguide 2 is 1.5 μm wide and is etched 4.5 μm deep. In the active waveguide, there is 0.1-μm-thick multiquantum-well (MQW) active layer on the

Manuscript received February 28, 2005; revised May 22, 2005. This work was supported by grants from Defense Advanced Research Projects Agency (DARPA) CS-DWDM Program, by UC MICRO/Oplink Grant, and by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD, Basic Research Promotion Fund; M01-2003-000-10195-0).

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Digital Object Identifier 10.1109/LPT.2005.853033

top of the of the waveguide core. MQW region consists of seven 65-A-thick quantum wells separated by 80-A-thick barriers [2]. The active waveguides are used in SOA sections only. MMI is made out of deeply etched narrow passive material. The length of an MMI scales with the square of its width. Therefore, one can reduce the length of the MMI by reducing its width. Width reduction is achieved by deep etching the MMI section. For the devices reported here, MMI width and length are 9 and 113 μm, respectively. This is among the shortest ever reported for this material system [3]. Passive waveguide 1 and 2 are connected through 15-μm-long linear width tapers shown in Fig. 1(a). The excess loss of these tapers is about 0.5 dB based on finite-difference time-domain simulations. The four mirrors complete the resonator. Two of the mirrors attached to input and output of the MMI connect passive waveguide 2 and 1 with a 90° bend. These are called small TIR mirrors. The two other mirrors before and after the SOA inside the ring connect passive waveguide 1 types through a 90° bend and are called big TIR mirrors. The big TIR mirrors were fabricated and tested separately earlier and had losses of about 0.7 dB per mirror [4]. The issues involved in the design and fabrication of such TIR mirrors are described in [5]. The small TIR mirrors are expected to have slightly higher loss due to slight mode shape mismatch between passive waveguide 1 and passive waveguide 2 modes after the taper. In this design, the presence of the SOA inside the resonator can be used to tune resonator properties by changing the SOA gain [6]. These resonators have a circumference of about 2.5 times smaller than recently fabricated resonators using MMIs made out of passive waveguide 1 type waveguides [7]. The fabrication starts with the growth of the base material up to the position indicated by the horizontal arrow in Fig. 1(b). Then active material is etched in areas where it is not desired. This is followed by the regrowth p-layers. The rest of the fabrication involves well-known reactive ion etching and metallization steps.

III. Results and Discussion

Filter characteristics are measured using another SOA integrated with the resonator as a broad-band source [8]. This SOA is not shown in Fig. 1(a), but has exactly the same design as the SOA inside the resonator. In the measurements, this SOA bias is kept fixed at 140 mA. Fig. 2(a) shows the variation of one of the resonances as the current of the SOA inside the resonator changes. When there is no bias, very little filtering is observed. This is due to strong absorption of the SOA inside the resonator. As the SOA current increases, first transparency is reached and then net gain is generated. This reduces the round-trip loss inside the resonator and the extinction ratio increases while the bandwidth gets smaller. As a result, quality factor of the resonator improves significantly. The resonance wavelength also moves toward shorter wavelengths. This is due to reduction of the index of refraction of the SOA section under current injection. Carrier injection reduces the index of refraction mainly due to plasma effect. The group index changes from 3.778 to 3.752 as current injection increases from 2 to 14 mA based on the modeling described later. The resonance wavelength shift reduces as current increases. Fig. 2(b) shows the variation of the resonances

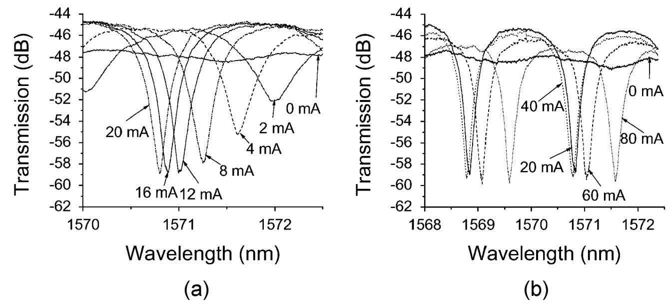

Fig. 2. Variation of the resonator transmission for different SOA currents within the resonator.

at higher SOA currents. The resonances shift slightly to shorter wavelengths as SOA current increases from 20 to 40 mA. For increased SOA current, there is a drastic shift toward longer wavelengths. This is due to heating. As power dissipation increases, the SOA section heats and the bandgap of the material shrinks. This increases the index of refraction which competes with the index of refraction decrease due to carrier injection. Heating slows the index decrease and eventually negates as current increases. Heating induces index increase and dominates at high currents. Furthermore, as current increases from 20 to 80 mA, neither the extinction ratio nor the bandwidth changes. This is due to gain saturation of the SOA. Round-trip loss in the resonator remains the same but the index of the SOA section keeps increasing due to heating. Therefore, the characteristic does not change but merely shifts toward longer wavelengths. The free spectral range of the resonator is 2 nm and the extinction ratio is about 14 dB. The full-width at half-maximum is about 0.3 nm, and finesse and Q-factor are more than 6 and 4900, respectively.

In order to determine the critical parameters of the resonator, we used modeling. The transmission through a ring resonator can be expressed as

$$\frac{P_{\text{out}}}{p_{\text{in}}} = \left| \frac{t - (t^2 + k^2)e^{-(\alpha_R + j\phi_R)}}{1 - te^{-(\alpha_R + j\phi_R)}} \right|^2 = \left| \frac{\sqrt{1 - k^2 - \gamma^2} - (1 - \gamma^2)e^{-(\alpha_R + j\phi_R)}}{1 - \sqrt{1 - k^2 - \gamma^2}e^{-(\alpha_R + j\phi_R)}} \right|^2.$$

In this equation, t and k are the field transmission and coupling coefficients of the MMI coupler, α_R is the round-trip field loss coefficient, and ϕ_R is the round-trip phase. This equation assumes that the coupler has some loss and $k^2 + t^2 + \gamma^2 = 1$, where γ^2 is the fraction of the power lost through the coupler. The measured characteristics at different SOA current levels are fitted to this equation and k^2 and α_R are determined as a result of this curve fitting. Fig. 3 shows the variation of the round-trip loss of the resonator as a function of the SOA current. This figure shows two curves obtained using the curve fitting technique around two adjacent resonances and their average. Curve fitting to different resonances yield slightly different results because of difficulty of making accurate measurements around transmission minimum points. For the SOA design used in the experiments, we expect the transparency current around 2 mA [2]. The round-trip loss at this point is about 6 dB. At SOA transparency, the round-trip loss is dominated by the loss of the four mirrors, passive waveguide loss, and the taper losses. The loss

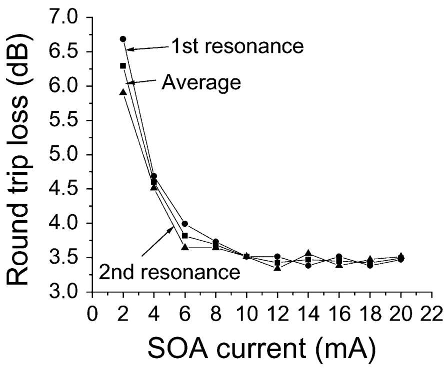

Fig. 3. Variation of the round-trip loss of the resonator for different SOA currents within the resonator based on curve fitting the characteristics shown in figure to the expected functional form.

of four TIR mirrors is about 4.4 dB assuming 1.6-dB propagation and taper loss. Assuming big TIR mirrors have a loss of 0.7 dB per mirror, we estimate the loss of small TIR mirrors as 1.5 dB per mirror. As the current increases, the gain of the SOA eventually saturates and the round-trip loss remains unchanged around 3.5 dB. The saturated gain of the SOA is about 2.5 dB, which is rather low. This is due to heating since the p-contact was at the top and the substrate was not thinned. This argument is supported by the variation of the resonance wavelength with increased current described earlier. The curve fitting also yields the power coupled per pass k^2 as 0.42 at all SOA currents. To reach critical coupling at this coupling level would require a round-trip loss of about 2.4 dB. In this experiment, we are not able to reduce the loss further to achieve critical coupling, but it should be easily achievable using a better heat sink SOA.

IV. Conclusion

We have fabricated and characterized novel ring resonators formed using four TIR mirrors. Such resonators can be scaled down to very small sizes since the round-trip loss is dominated by the mirror loss and has very slight dependence on the total circumference of the cavity. The average loss per mirror is determined to be about 1.1 dB per mirror. Coupling in and out of such resonators is done using very compact MMI couplers of length 113 μm. Since this coupling is lateral, one can use the same material platform and process steps used for the fabrication of other active and passive devices making direct integration possible. Furthermore, regular rib waveguides optimized for high gain can be used within the resonator. The only additional processing step is a deep etch to fabricate the TIR mirrors. This integration is demonstrated by integrating an SOA within the cavity. Such SOA integration has the added advantage of tuning the resonator properties by changing the gain of the SOA. Strong tuning of the on–off ratio and the resonance wavelength were also demonstrated. This technology has other possible applications. For example, integrating another SOA before the resonator forms a cross-gain-modulation-based wavelength converter.

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