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Micro-Racetrack Notch Filters Based on InGaAsP/InP High Mesa Optical Waveguides

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1. Introduction

Micro resonators based on high-index contrast waveguides are attractive components to realize photonic integrated circuits [1]. Furthermore, in the application of wavelength division multiplexing (WDM) components, they are promising candidates for the optical filters with high finesse filter characteristics. InP-based devices have been investigated for the application due to the availability of materials lattice matched to InP which can emit, absorb, and modulate long wavelength (1.55μm) lightwave signal. Micro-resonator based devices can be divided into two types in terms of coupling strategies between the bus waveguides and ring resonators: these are vertically-coupled and laterally-coupled ring resonators. Vertically coupled devices have demonstrated excellent performance in filters and modulators and have advantages of tight control of gap spacing between the bus waveguides and micro rings. However, they require highly controllable wafer bonding or wafer fusion technique for their fabrication [2]. Laterally-coupled ring resonators are very interesting because dissimilar passive and active devices can be integrated with the resonators on the same chip but they require fabrication techniques such as nanoscale lithography as well as highly anisotropic etching. It is critical to control gap spacings between the bus waveguides and ring resonators to fabricate high performance notch filters based on laterally coupled ring resonators.

In the case of the close-type laterally-coupled single micro-racetrack resonators, the amplitude transmittance can be expressed as follows,

$$T=\frac{\tau-\rho\exp(-j\beta L)}{1-\tau\rho\exp(-j\beta L)},\quad \tau=\sqrt{1-\kappa^2},\quad \rho=e^{-\alpha L/2} \qquad (1)$$

where κ^2 is a fraction of power coupled from bus waveguide into the racetrack resonator, ρ is the amplitude after a round-trip, L is the circumference of the racetrack resonator, β is the propagation constant in the racetrack resonator waveguide, respectively [2,3]. For the critically-coupled case where τ is equal to ρ, the on-resonance intensity transmittance, $|T|^2$, drops to zero so that the extinction ratio goes to infinity. Therefore, the quality of the filter response is critically dependent on matching between τ and ρ. Filter performance such as extinction ratio degrades when mismatch between τ and ρ increases. However, it is not easy to accomplish desired resonant characteristics, because τ and ρ are are affected by processing conditions as well as device design. It is interesting to design a filter with good extinction ratio without requiring critical coupling condition between racetrack resonators and bus waveguides. In this study, three racetrack resonators with different gap spacings between racetrack resonators and bus waveguides are cascaded to improve extinction ratio.

2. Experiment

Various single and third-order laterally-coupled micro-racetrack resonators in InGaAsP/InP heterostructures were fabricated by utilizing nanoscale e-beam lithography and Cl_2-based inductively-coupled-plasma reactive ion etching (ICP-RIE) [4]. Waveguide heterostructures and the fabricated micro-racetrack resonator coupled waveguides are shown in Fig. 1. The fabricated first-order and third-order notch filters are shown in Fig. 2 (a). In this third-order device, the total filter response is the product of cascaded filter's response. Therefore, high order filters are expected to exhibit improved extinction ratio at the resonance wavelengths. The bus and racetrack waveguides have the same widths, and all the racetrack resonators have an identical radius of 9.32-μm with 50-μm-long straight waveguide sections, but the gaps between the bus waveguide and racetrack resonators are different. The detailed dimensions of various notch filters are tabulated in Table 1.

The measurements to obtain spectral responses of micro-racetrack notch filters were performed at C-band. The wavelengths of TM-polarized (E_y) input lightwave were tuned with 10 pm-steps by utilizing a tunable external cavity laser. The input and output light coupling was carried out by utilizing tapered optical fibers with nominal spot size of 1.7 μm.

3. Results and Discussion

From the measured finesse and extinction ratio values for resonator-coupled waveguides with different gap spacings, τ's and ρ's were extracted by using graphical methods. In Fig. 3 (a), the possible combinations of τ's and ρ's are presented for various values of extinction ratio and finesse in over-coupled regime. The intersection of extinction ratio and finesse curves indicates corresponding combination of

τ and ρ. In this calculation process, it was assumed that α is identical for first-order and third-order resonators with the same waveguide width, and κ decreases with increasing gap spacing between the bus waveguide and the racetrack resonator. The calculated results are presented together with the critical dimensions of the first-order and third-order notch filters in Table 1. In the case of first-order notch filter with gap spacing of 0.47 μm, the corresponding ρ and τ were extracted value from the measured spectral responses of other first-order and third-order notch filters because of its poor filter characteristics insufficient to get correct extinction ratio and finesse.

As shown in Table 1, the first-order filters with different gap spacings had similar ρ and quite different τ values as expected. From these results tabulated in Table 1, the desired gap spacing for critical coupling is expected to be in between 0.18 μm and 0.36 μm. As shown in Fig. 3 (b), near the critical coupling condition, large extinction ratio over 40 dB is expected. By cascading three of these first-order racetrack resonators, the third-order notch filter achieved an 18.9 dB of extinction ratio and 5.3 of finesse. Even though all the racetrack resonators coupled to the bus waveguide do not satisfy critical coupling condition, the designed filter exhibits good extinction ratio.

4. Conclusions

First and third-order micro-racetrack notch filters based on InGaAsP/InP high mesa optical waveguides were successfully fabricated and characterized. By cascading ring resonators, reasonable filter characteristics could be achieved even though critical coupling condition was not warranted. The performance of the high order filter in this study is much less sensitive to the fabrication process.

Acknowledgements

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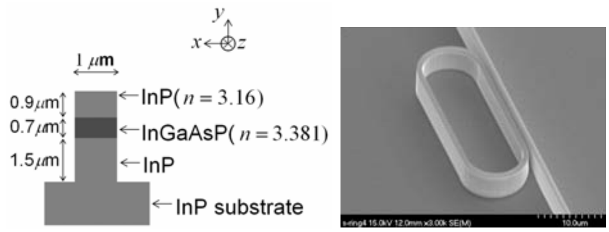

Fig. 1 (a) Heterostuctures of InGaAsP/InP high mesa optical waveguides and (b) SEM micrgragh of fabricated single micro-racetrack notch filter

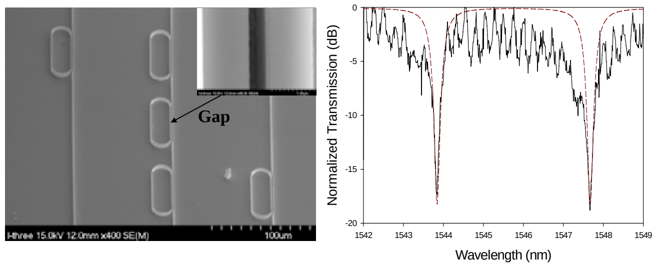

Fig. 2 (a) Scanning electron micrgragh of the fabricated first- and third-order microracetrack notch filters and (b) Normalized intensity transmittance of third order micro racetrack resonator: measured (—) and fitted (---) spectral responses

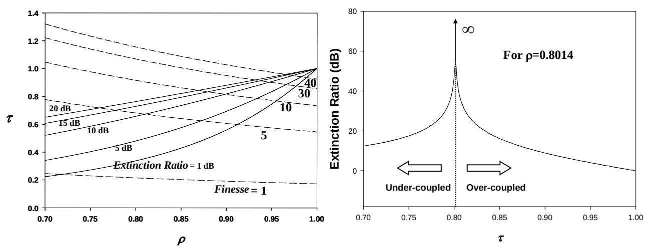

Fig. 3 (a) The relationship between ρ and τ in terms of extinction ratio and finesse at over-coupled regime and (b) Caculated extinction ratio as a function of τ (for ρ = 0.8014)

Table I Summary of dimensions and filter characteristics of micro-racetrack notch filters

Waveguide width	1 μm			
Type	1st-order			3rd-order
Gap (μm)	0.18	0.36	0.47	-
Extinction Ratio (dB)	10.02	8.043	-	18.856
Finesse	6.919	11.532	-	5.283
τ	0.7181	0.9081	0.994	-
ρ	0.8398	0.8014	0.7923	-
State	Over coupled	Under coupled	Under coupled	-