MMI-Coupled Ring Resonators in GaInAsP–InP

Dominik G. Rabus and Michael Hamacher

***Abstract*—The characteristic response of single and double GaInAsP–InP ring resonators in the form of race tracks with a radius of 100 and 200 μm are presented. The used multimode interference (MMI) coupler is as short as 150 μm. A contrast of 13 dB, a finesse of six, and free spectral ranges of 50 and 100 GHz have been achieved for the single ring resonator. The double ring resonator has a full-width at half-maximum (FWHM) of 0.25 nm for the throughput port and 0.4 nm for the drop port.**

***Index Terms*—Filter, GaInAsP–InP, MMI, resonator, ring.**

I. Introduction

ACTIVE and passive ring resonator devices are promising candidates for wavelength filtering, routing, switching, modulation, and multiplexing/demultiplexing applications. Ring resonators do not require facets or gratings for optical feedback and are thus particularly suited for monolithic integration with other components. In addition, they are rather robust with respect to back reflections. Devices in the AlGaAs–GaAs [1], [10], Si–SiO_2 [2] and GaInAsP [3] material system have already been reported in the past.

The present letter focuses on single and double ring resonators (DRRs) in GaInAsP–InP. In particular, we report their fabrication, characterization and a comparison of experimental data with simulations.

II. Design and Fabrication

The layer sequence of the devices is as follows: InP substrate, GaInAsP ($\lambda_{gap} = 1.06$ μm, 0.38 μm), InP etch stop layer, GaInAsP ($\lambda_{gap} = 1.06$ μm, 0.84 μm), InP cap (0.2 μm). The design assures both a monomodal propagation of the light in the waveguide and, due to a good confinement, very low bending losses. Additionally, the rings were deeply etched along the outer wall of their curved sections, as previously reported in [3]. The waveguide width is 1.8 μm (Fig. 1). The effective index of the straight waveguide without deep etching was calculated to be 3.19 at a wavelength of 1.55 μm. There are two possibilities to couple light into the resonator, using a well-known multimode interference (MMI) coupler that is tolerant with respect to the 3-dB splitting ratio or a conventional directional coupler if other coupling ratios are needed. We used a compact 3-dB MMI coupler with a length of 150 μm and a width of 6 μm.

The ring resonators were structured using standard photolithography and a CH_4/H_2 reactive ion etching technique. SiN_x was used as etching mask, which also served as the mask for the deep etching process. In order to reduce the formation of polymers during dry etching and so to minimize the sidewall roughness a small fraction of oxygen was added. A photograph of a manufactured ring resonator is shown in Fig. 2. The facets of the input and output waveguides have been antireflection coated in order to avoid Fabry–Perot resonances in the straight waveguide section. A SEM picture of a curved, deep etched waveguide and of a MMI section is shown in Fig. 3.

Manuscript received September 25, 2000; revised April 26, 2001.

The authors are with the Heinrich-Hertz-Institut fuer Nachrichtentechnik Berlin GmbH, 10587 Berlin, Germany.

Publisher Item Identifier S 1041-1135(01)06635-6.

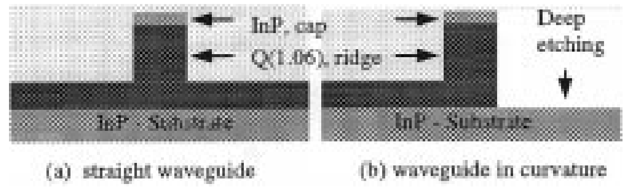

Fig. 1. Schematic cross-section diagram of the used waveguides.

III. Simulation

Recent achievements in technology enable the realization of micrometer-sized structures with sufficient quality. Therefore, also the mathematical analysis of ring resonators has gained new attraction [4]. We have used the method given in [5], [6] to describe a single ring resonator (SRR). The equation for the transmission of the output field is given by

$$\frac{E_t}{E_i} = D \cdot \left[\frac{y - x \cdot \exp(j \cdot \Phi)}{1 - y \cdot x \cdot \exp(j \cdot \Phi)} \right] \quad (1)$$

where D is the intensity loss coefficient of the MMI (in the lossless case $D = 1$).

$$\begin{aligned} x &= D \cdot \exp(-\alpha \cdot L) \\ y &= \sqrt{1 - \kappa} \\ \Phi &= k_n \cdot L \end{aligned} \quad (2)$$

where κ is the power coupling coefficient, L is the length of the ring resonator, α is the insertion loss coefficient of the ring, k_n is the wave propagation constant, E_t is the transmitted and E_i is the inserted electric field.

The transmission of the output intensity is given by [6]

$$\frac{I_t}{I_i} = \left| \frac{E_t}{E_i} \right|^2 = D^2 \cdot \left[1 - \frac{(1 - x^2) \cdot (1 - y^2)}{(1 - x \cdot y)^2 + 4 \cdot x \cdot y \cdot \sin^2 \left(\frac{\Phi}{2} \right)} \right] \quad (3)$$

where I_t is the transmitted and I_i is the inserted intensity, respectively. The resonance wavelength spacing, $\Delta\lambda$ and the full-width at half-maximum (FWHM) are given by

$$\Delta\lambda = \left| \frac{\lambda^2}{n_{gr} \cdot L} \right| \quad (4)$$

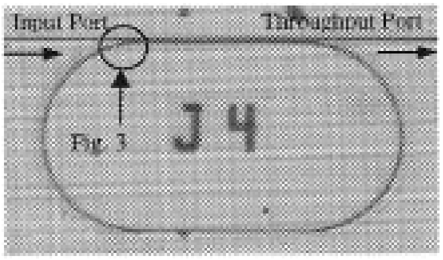

Fig. 2. Photograph of a ring resonator with $R = 100$ μm.

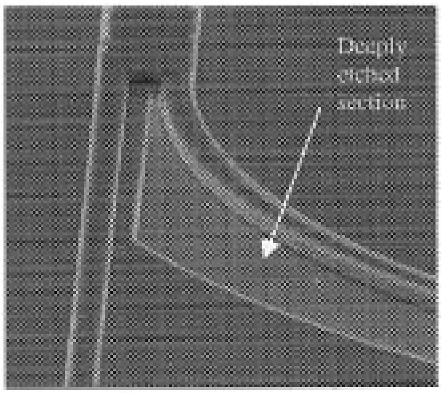

Fig. 3. SEM of the input region of a MMI coupler.

$$\mathrm{FWHM} = \frac{\lambda^2}{F \cdot n_{gr} \cdot L} \tag{5}$$

where F is the finesse of the resonator and n_{gr} is the group index. Using these equations, it is possible to simulate the spectral response of the ring resonator.

IV. Results and Conclusion

A. Single Ring Resonator (SRR)

The ring resonators were characterized using a tapered fiber and an external cavity laser. The ring resonators under investigation here are polarization dependent due to waveguide asymmetry. This is of no relevance, if the ring resonators comprise an active section and act as a laser. Polarization dependent filter characteristics can be eliminated by a polarization diversity architecture. InP-based integrated polarization rotators and splitters required for this design have already been developed in the past [7], [9]. The measurements reported here have been performed for TE polarization. The response from the throughput port of a ring resonator with a radius R of 100 and 200 μm is shown in Figs. 4 and 5, respectively. As designed, a FSR of approximately 0.8 nm (100 GHz) for the 100-μm ring device and 0.4 nm (50 GHz) for the 200-μm device are observed near $\lambda = 1.55$ μm. The insertion losses of the two devices are between 7–8 dB (including the coupling losses of approximately 5 dB). The waveguide losses in GaInAsP were determined to be around 1 dB/cm, and so the insertion losses for these devices are comparable to those of a straight waveguide that has approximately the same value. By comparing the measurement with the simulation, the value for α obtained is approximately 1 cm^{-1} for both of the rings. The transmission difference between the minima and the off-resonant values for $R = 100$ μm

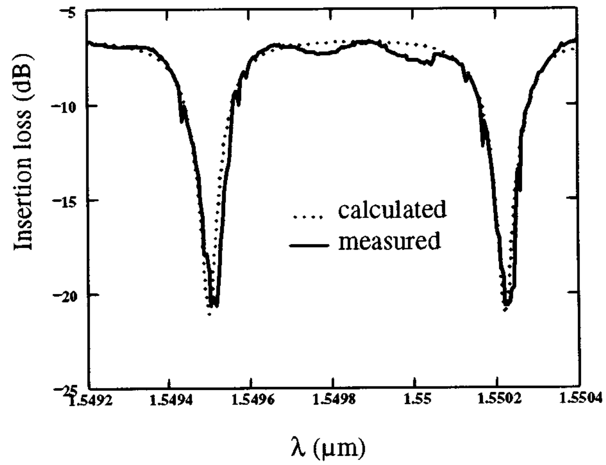

Fig. 4. Results of a ring resonator with $R = 100$ μm.

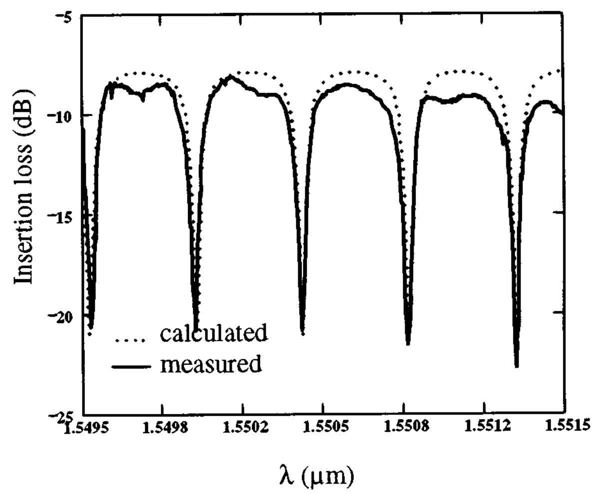

Fig. 5. Result of a ring resonator with $R = 200$ μm.

and $R = 200$ μm rings are more than 13 dB. These deep minima signify that most of the power on the input port is extracted at resonance. The group index of these devices was calculated from the experimental values to be 3.49 near 1.55-μm wavelength. The FWHM for $R = 100$ μm and $R = 200$ μm devices were observed to be approximately 0.14 and 0.08 nm, respectively. This leads to a finesse of nearly six for these devices. The SRRs are suitable for laser applications due to the small FWHM. For optical filters, multiple cascaded ring resonators have to be used.

B. Double Ring Resonator (DRR)

Steeper rolloff and out-of-band rejection are needed for filter applications and one solution is to couple ring resonators in series. A DRR was thus fabricated (Fig. 6) and characterized in the same way as the SRRs. The two rings of the DRR with $R = 100$ μm were coupled using three MMIs with a length of 150 μm, leading to a FSR of 100 GHz.

The experimental results were simulated according to the equations described in Section III and results are shown in Fig. 7.

The insertion loss was 7 dB, which is comparable to those of the SRR. The contrast of the throughput port and of the drop

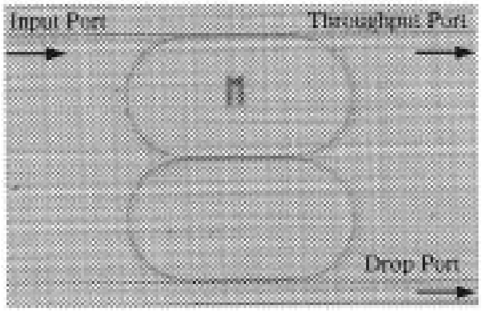

Fig. 6. Photograph of a DRR with $R = 100$ μm.

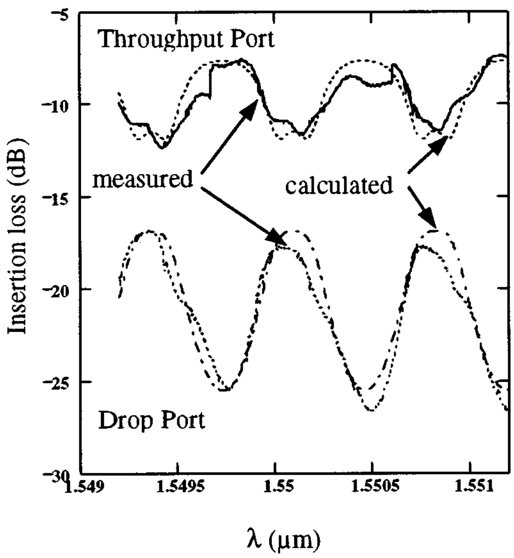

Fig. 7. Result of a DRR with $R = 100$ μm.

port are around 3.5 and 7.5 dB, respectively. As DRRs comprise 3 MMIs, their total loss is rather likely to prevent the fabrication of high contrast filters, even if the MMI losses correspond to the current state of the art. The calculated value for α was 1.4 cm^{-1}. The expected broadening of the FWHM for the throughput port was measured to be 0.25 nm and of the drop port 0.4 nm. In order to improve the contrast for system applications and to compensate the losses of the device, gain sections have to be implemented into the ring. To assure precise 100-GHz channel spacing, the resonators' optical length can be trimmed by, for example, the electrooptic effect.

V. Conclusion

In conclusion, passive MMI-coupled GaInAsP–InP SRRs and DRRs with free spectral ranges of 50 and 100 GHz were fabricated and characterized. The power at the throughput port at resonance for the SRR was measured to be lower than -13 dB from off-resonant values, indicating that most of the power in the input waveguide is extracted by the ring. The DRR showed the expected broadening of the FWHM, which is essential for most systems applications. The values were 0.25 nm for the throughput port and 0.4 nm for the drop port. The simulated results coincide very well with experimental values and are a good tool for the further design of ring resonators. In varying α, the coupling factor, the length and using multiple resonators, tailored passband characteristics can be realized. We believe that passive and active (including gain sections) mono and multiring resonator circuits will become an important component family in optical signal processing applications. These results are a first step toward the realization of active multiring resonator circuits used in optical networks.

Acknowledgment

The authors wish to acknowledge fruitful discussions and support of the MIRO-Project Group, at the Heinrich-Hertz-Institut, funded by the German Ministry of Development and Research. The authors would also like to thank H. Heidrich for helpful discussions.

References

[1] S. C. Hagness, D. Rafizadeh, S. T. Ho, and A. Taflove, "FDTD microcavity simulations: Design and experimental realization of waveguide-coupled single-mode ring and whispering-gallery-mode disk resonators," *J. Lightwave Technol.*, vol. 15, pp. 2154–2164, Nov. 1997.

[2] B. E. Little, J. S. Foresi, G. Steinmeyer, E.R. Theon, S. T. Chu, H. A. Haus, E. P. Ippen, L. C. Kimerling, and W. Greene, "Ultra-compact Si-SiO_2 ring resonator optical channel dropping filters," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 549–551, Apr. 1998.

[3] G. Griffel, J. H. Abeles, R. J. Menna, A. M. Braun, J. C. Connolly, and M. King *et al.*, "Low-threshold InGaAsP ring lasers fabricated using bi-level dry etching," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 146–148, Feb. 2000.

[4] G. Griffel, "Synthesis of optical filters using ring resonator arrays," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 810–812, July 2000.

[5] A. Yariv, "Universal relations for coupling of optical power between microresonators and dielectric waveguides," *Electron. Lett.*, vol. 36, no. 4, pp. 321–322, 2000.

[6] K. Okamoto, *Fundamentals of Optical Waveguides*. San Diego, CA: Academic, 2000.

[7] H. Heidrich, P. Albrecht, M. Hamacher, H.-P. Nolting, H. Schroeter-Janssen, and C. M. Weinert, "Passive mode converter with a periodically tilted InP/GaInAsP rib waveguide," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 34–36, Jan. 1992.

[8] B. E. Little and S. T. Chu, "Theory of loss and gain trimming of resonator-type filters," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 636–638, June 2000.

[9] R. Kaiser *et al.*, "Heterodyne receiver PIC's as the first monolithically integrated tunable receivers for OFDM system applications," *Opt. Quantum Electron.*, vol. 28, pp. 565–573, 1996.

[10] D. V. Tishinin, P. D. Dapkus, A. E. Bond, I. Kim, C. K. Lin, and J. O'Brien, "Vertical resonant couplers with precise coupling efficiency control fabricated by wafer bonding," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 1003–1005, Aug. 1999.

[11] J. V. Hryniewicz, P. P. Absil, B. E. Little, R. A. Wilson, and P.-T. Ho, "Higher order filter response in coupled microring resonators," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 320–322, Mar. 2000.