# BOX-LIKE FILTER RESPONSE OF TRIPLE RING RESONATORS WITH INTEGRATED SOA SECTIONS BASED ON GaInAsP/InP

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Abstract

Triple coupled ring resonator (TRR) add/drop filters with parallel and serial configurations with integrated semiconductor optical amplifiers (SOAs) were designed and fabricated. The implemented SOAs within the resonators offer loss compensation plus additional device functionality. The high order filters have passband characteristics with sharper roll-off, flatter tops, and greater out-of-band rejection than previously demonstrated first order ring resonator filters. The free spectral range (FSR) of the devices is 25 GHz and 50 GHz. An on-off ratio of more than 20 dB was realized. The characteristic response of designed and manufactured triple ring resonator filters with codirectional couplers and integrated semiconductor optical amplifiers are presented.

## I. Introduction

Wavelength division multiplexing (WDM), especially dense wavelength division multiplexing (DWDM) communication systems require optical components which can de-/multiplex closely spaced channels. A filter referred to as an add/drop filter is required to separate the channel to be dropped from those that pass through unaffected. Channel dropping filters on the basis of ring resonators have attracted attention recently (1), (2), (3), (4). Closer channel spacing (e.g. 50 GHz and 25 GHz) requires sharper filter responses. Realizing on-off ratios of > 20 dB to separate the channels without introducing crosstalk from the other channels which can be realized using multiple coupled ring resonators (5) gets technologically more demanding the smaller the channel separations are.

In this paper, we report the realization of loss compensated, high order ring resonator filters for use as WDM optical signal channel dropping filters.

## II. Design and fabrication

The passive sections of the devices consist of: InP substrate, GaInAsP ($\lambda_{gap}$=1.06 µm, thickness (t): 0.38 µm), InP etch stop layer (t: 0.020 µm), GaInAsP ($\lambda_{gap}$=1.06 µm, t: 0.84 µm), InP cap (t: 0.2 µm). The waveguide design assures both, a monomodal propagation of the light in the waveguide and, due to a good confinement, low bending losses. Additionally, the waveguide ridge was deeply etched at the outer side of the waveguide in the curvatures (Fig. 1). The waveguide width is 1.8 µm. Pt – resistors for resonance matching and wavelength tuning (6) were deposited on top of the waveguide in the straight sections in the ring resonators and in the case of the parallel configuration also on top of the interconnecting straight waveguides.

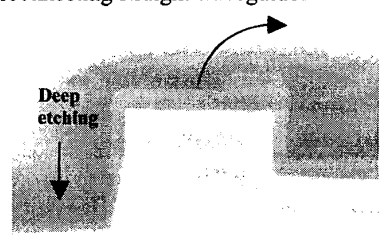


Fig. 1. Scanning electron microscope (SEM) picture of a deeply etched waveguide in the curvature.

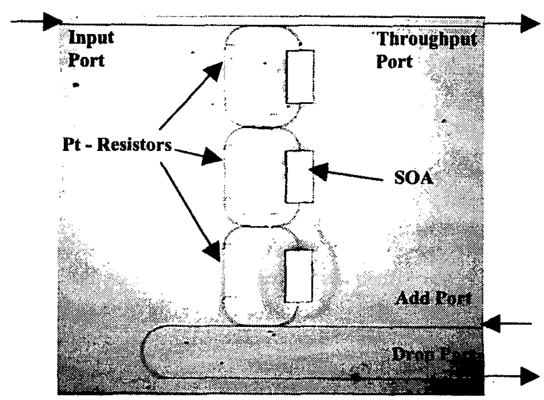


Fig. 2. Photograph of a fabricated serially coupled triple ring resonator.

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Photographs of the fabricated triple ring resonator configurations are shown in Fig. 2 and Fig. 3. A standard ridge waveguide laser structure was used for the SOA section, which required an additional epitaxial growth step. The layer sequence of the ridge waveguide structure from top to bottom is: GaInAs (t: 0.2 μm), InP (t: 1.3 μm), 6 quantum wells ($\lambda_{gap}$=1.29 μm t: 36 nm), n-GaInAsP (t: 0.2 μm), InP-substrate. The facets of the input and output waveguides have been antireflection coated in order to avoid Fabry-Perot resonances in the straight waveguide section.

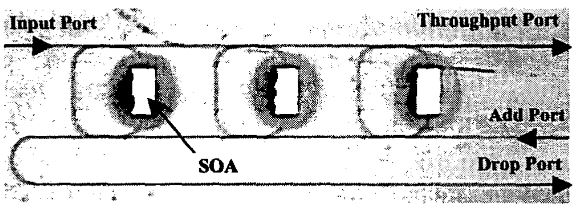


Fig. 3. Photograph of a fabricated parallel coupled triple ring resonator.

## III. Simulation

The calculation model takes into account the presence of active sections, tuning of the refractive index in one part of the resonator due to local heating, transition losses at the active/passive interface, at the interface straight/curved waveguide section, coupling losses and material losses in each segment. In order to account for these specific details, the ring resonator configuration is separated into different segments as demonstrated in [7]. The electric field of the traveling wave in each segment is described by the following equation:

$$E_{Segment} = E_A \cdot exp^{-\frac{\alpha_{Segment}}{2} L_{Segment} - jk_{n\,Segment} L_{Segment}} \quad (1)$$

where $E_A$ is the amplitude of the electric field , $\alpha_{Segment}$ is an intensity attenuation coefficient, $L_{Segment}$ is the length and $k_{n\ Segment}$ is the wave propagation constant of each segment. The box-like shape of the filter response for the drop port can be described by a shape factor [8] which is specified for the presented triple ring resonator configurations as:

$$\text{Shape factor} = \frac{\text{Bandwidth } L_1}{\text{Bandwidth } L_2} = \frac{\text{-15 dB Bandwidth}}{\text{-25 dB Bandwidth}} \quad (2)$$

The ideal response shape is a rectangular filter function with the shape factor of 1, with a flat pass band and a step-like roll-off from pass band to stop band.

The simulated practically feasible filter response of the drop port of a serially coupled TRR is shown in Fig. 4. The fiber-chip coupling losses are assumed to be 10 dB in the simulation. The shape factor of the simulated drop port filter response of the serially coupled TRR is calculated to be 0.6.

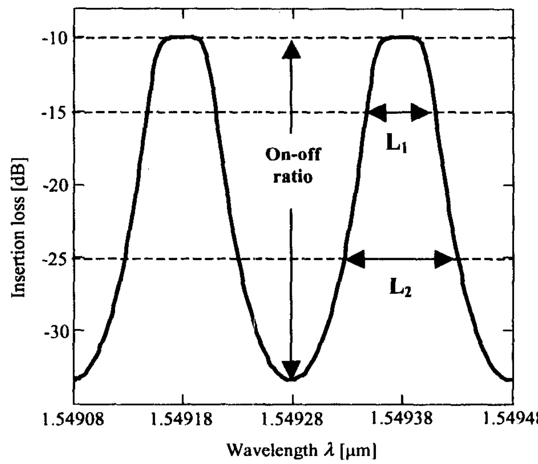


Fig. 4. Simulated filter response of the drop port of a serially coupled TRR with an FSR of 25 GHz.

The superposition of all possible resonating paths in multiple coupled ring resonators has to be considered. There are various combinations of resonating paths, for example, the first and the second ring resonator can be combined to form another resonating path. In an ideally designed multiple coupled ring resonator configuration all possible optical resonator lengths are identical or a multiple $N$ of each other due to the same effective refractive index. The simulated practically feasible filter response of the drop port of a parallel coupled TRR is shown in Fig. 5.

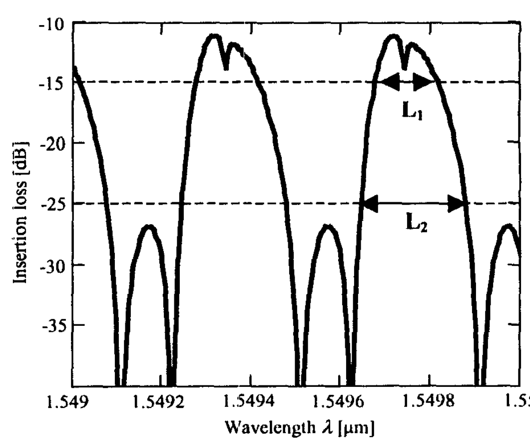


Fig. 5. Simulated filter response of the drop port of a parallel coupled TRR with an FSR of 50 GHz.

The ripples in the simulation are due to a difference in the optical lengths of the various resonating paths, for example $P_2 \neq N \cdot P_1$ (Fig. 6). This is due to a difference in the effective refractive index between the used passive waveguide and an SOA section leading to a different optical length.

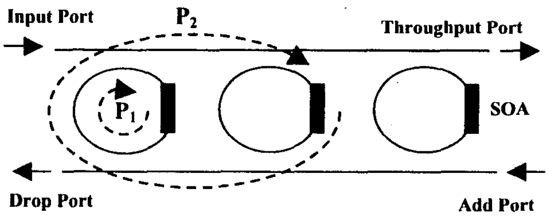


Fig. 6. Model of a parallel TRR with SOAs and different resonating optical paths $P_1$ and $P_2$.

In our case the slight resonance mismatch leads to the designed broadening and steep roll-off of the filter curve and so to a high shape factor. The shape factor of the simulated drop port filter response of the parallel coupled TRR is calculated to be 0.6. The drop port filter response of the triple ring resonator configuration is calculated for all involved ring resonators to be in phase.

## IV. Results on triple coupled ring resonators

The serially coupled TRR (cf. Fig. 2) has a radius of 323 µm. The length of an SOA is 400 µm. The coupler length is 325 µm and the coupling gaps from top to bottom are 0.8 µm, 1 µm, 1 µm, 0.8 µm. A scanning electron microscope picture of the input region of a codirectional coupler with a coupling gap of 0.8 µm is shown below.

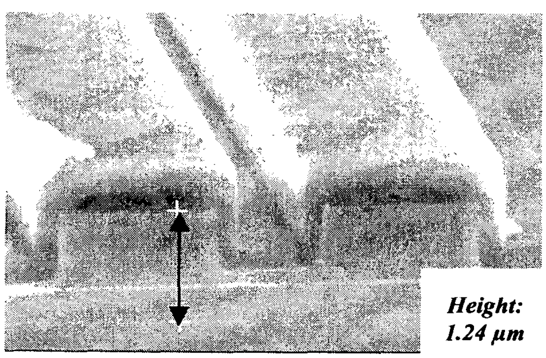


Fig. 7. SEM picture of a codirectional coupler with a coupling gap of 0.8 µm.

The FSR achieved is 25 GHz. The driving current for each of the three SOAs is 50 mA. The filter characteristic of the drop port is shown in Fig. 8. The shape factor for the drop port is measured to be 0.52. The ring resonators in the parallel configuration (cf. Fig. 3) have a radius of 117 µm, a coupler length of 200 µm (gap = 0.9 µm) and an SOA length of 300 µm. An FSR of 50 GHz has been realized. All SOAs are operated at an injection current of 50 mA. The filter characteristic of the drop port is shown in Fig. 9. The shape factor is measured for this configuration using the - 20 dB and - 30 dB bandwidths due to the ripples in the spectrum. The shape factor is measured to be 0.65 (calculated shape factor using the corresponding bandwidths = 0.75).

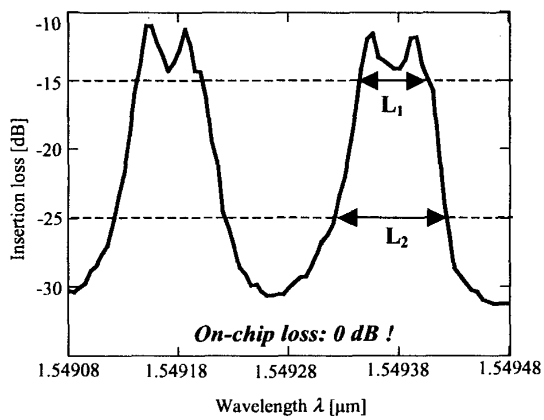


Fig. 8. Measured response of the drop port of a serially coupled TRR with integrated SOAs, radius of 325 µm, an SOA length of 400 µm and an FSR of 25 GHz.

The distance between the resonators is chosen to be equal to half of the circumference of a ring resonator.

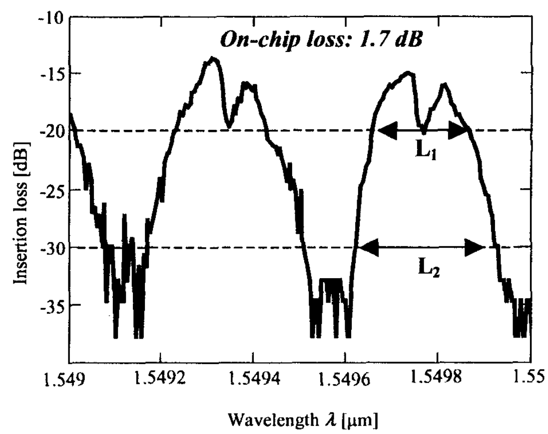


Fig. 9. Measured response of the drop port of a parallel coupled TRR with integrated SOAs, radius of 117 µm, an SOA length of 300 µm and an FSR of 50 GHz.

The difference between the calculated and the measured shape factors is due to a slight phase mismatch between all involved resonating paths in the measurements of the drop port filter responses of the ring resonator configurations. A measure of the on-chip loss of the filter can be obtained by comparing the maximum drop port power on resonance to the maximum throughput port power off resonance. For the parallel TRR configuration this ratio is 1.7 dB. The on-chip losses of the serially coupled TRR were fully compensated by the SOAs.

## V. Summary

In conclusion, we have demonstrated an improved filter response using loss compensated triple ring resonator configurations with integrated semiconductor optical amplifiers and codirectional couplers for performing well specified coupling conditions between the resonators. Free spectral ranges of 25 GHz and 50 GHz and on-off ratios of 20 dB for the serially and parallel coupled triple ring resonators, respectively, have been achieved. Accurate variation of the interresonator coupling strength modified the filter passband shape, and demonstrated the expected flattened response. Shape factors for the drop port of 0.52 and 0.65 for the serially and parallel coupled configuration respectively, have been realized using appropriate coupling factors.

The GaInAsP material system facilitates the integration of active elements like semiconductor optical amplifiers which are essential for realizing this type of optical filter with the demonstrated filter response. The use of multiple coupled ring resonators provides additional design flexibility to achieve various filter responses.

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## References

[1] D. G. Rabus and M. Hamacher, "MMI-Coupled Ring Resonators in GaInAsP-InP," IEEE Photon. Technol. Lett., vol. 13, no. 8, pp. 812-814, August 2001.

[2] R. Grover, P. P. Absil, V. Van, J. V. Hryniewicz, B. E. Little, O. King, L. C. Calhoun, F. G. Johnson, and P.-T. Ho, "Vertically coupled GaInAsP-InP microring resonators," Opt. Lett., vol. 26, no. 8, pp. 506-508, April 2001.

[3] Y. Kokubun, S. Kubota, S.-T. Chu, "Polarization-independent vertically coupled microring resonator filter," Electron. Lett., vol. 37, no. 2, pp. 90-92, January 2001.

[4] D. J. W. Klunder, E. Krioukov, F. S. Tan, T. Van der Veen, H. F. Bulthuis, G. Sengo, C. Otto, H. J. W. M. Hoekstra, A. Driessen, "Vertically and laterally waveguide-coupled cylindrical microresonators in $Si_3N_4$ on $SiO_2$ technology," Appl. Phys. B, vol. 73, pp. 603-608, November 2001.

[5] J. V. Hryniewicz, P. P. Absil, B. E. Little, R. A. Wilson, P.-T. Ho, "Higher Order Filter Response in Coupled Microring Resonators," IEEE Photon. Technol. Lett., vol. 12, no. 3, pp. 320-322, March 2000.

[6] D. G. Rabus, M. Hamacher, H. Heidrich, "Active and Passive Microring Resonator Filter Applications on GaInAsP/InP," Proc. IPRM'01, paper ThA1-3, pp. 477-480, May 2001.

[7] D. G. Rabus, M. Hamacher, H. Heidrich, "Resonance Frequency Tuning of a Double Ring Resonator on GaInAsP/InP: Experiment and Simulation," Jpn. J. Appl. Phys. (JJAP), Part 1, vol. 41, no. 2, pp. 1186-1189, February 2002.

[8] Y. Yanagase, S. Suzuki, Y. Kokobun, S.-T. Chu, "Box-like Filter Response by Vertically Series Coupled Microring Resonator Filter," Proc. ECOC'01, Paper Th.A.3.3, pp. 634-635, October 2001.