

## Resonance Frequency Tuning of a Double Ring Resonator in GaInAsP/InP: Experiment and Simulation

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(Received June 18, 2001; accepted for publication October 4, 2001)

A racetrack shaped double ring resonator (DRR) filter is demonstrated with radii of  $200\ \mu\text{m}$ . The double ring resonator contains two  $-3\ \text{dB}$  multimode interference (MMI) couplers for I/O coupling and a  $-13\ \text{dB}$  codirectional coupler in between the rings. A free spectral range of  $50\ \text{GHz}$  has been realized. A simulation model has been developed to describe the DRR. As fabrication tolerances do not allow the realization of two identical rings with required nm-circumference accuracy in the resonator, a frequency alignment of the resonator is indispensable. The resonance frequency tuning is performed thermally using platinum resistors which have been placed on top of the waveguides in both rings. An on-off ratio increase has been achieved of more than  $3\ \text{dB}$ , resulting in a total on-off ratio larger than  $18\ \text{dB}$ . The frequency alignment is inevitable in the case of multiple coupled micro ring resonators. [DOI: 10.1143/JJAP.41.1186]

KEYWORDS: ring, resonator, filter, resonance, tuning, GaInAsP, InP

### 1. Introduction

Active and passive ring resonator devices are promising candidates for wavelength filtering, routing, switching, modulation, and multiplexing/demultiplexing applications.<sup>1)</sup> Ring resonators do not require facets or gratings for optical feedback and are particularly suited for monolithic integration with other components. The passband shape of ring resonator filters can be custom designed by the use of multiple coupled resonators. The filter characteristic (steep roll-off, flat top and high contrast  $> 20\ \text{dB}$ ) depends on the energy flow in the resonators which defines the desired filter shape. It is necessary to achieve smooth sidewalls for low waveguide losses, deep etched curvatures for low bending losses and precise waveguide dimensions for power splitting.<sup>2)</sup> Steeper roll-off and out-of-band rejection require cascaded micro-ring resonators.<sup>3)</sup> The implementation of gain sections within the ring resonator opens the possibility to adjust the energy flow for optimum response.<sup>4)</sup> The matching of the resonance frequency of each ring in multiple coupled ring resonators is inevitable to achieve the desired filter characteristic. The present paper focuses on the frequency matching in a double ring resonator configuration in GaInAsP/InP, using platinum resistors. An adequate simulation model has been developed to describe the characteristic of the double ring resonator.

### 2. Simulation Model

The behavior of single and multiple coupled ring resonators can be described by several methods and models.<sup>5-7)</sup> The model which has been used in the following calculations is shown in Fig. 1. The resonator is separated into different segments in order to describe the waveguide behavior in terms of loss, dispersion, effective index and optical length. The electric field of each segment can be approximated by:

$$E_{\text{Segment}} = \exp(-\alpha \cdot L + j \cdot k \cdot L) \quad (1)$$

$$k = \frac{2\pi \cdot n_{\text{eff}}}{\lambda} \quad (2)$$

where  $\alpha$  is the waveguide loss coefficient,  $L$  is the length,  $n_{\text{eff}}$  is the effective index of each segment and  $\lambda$  is the wave-

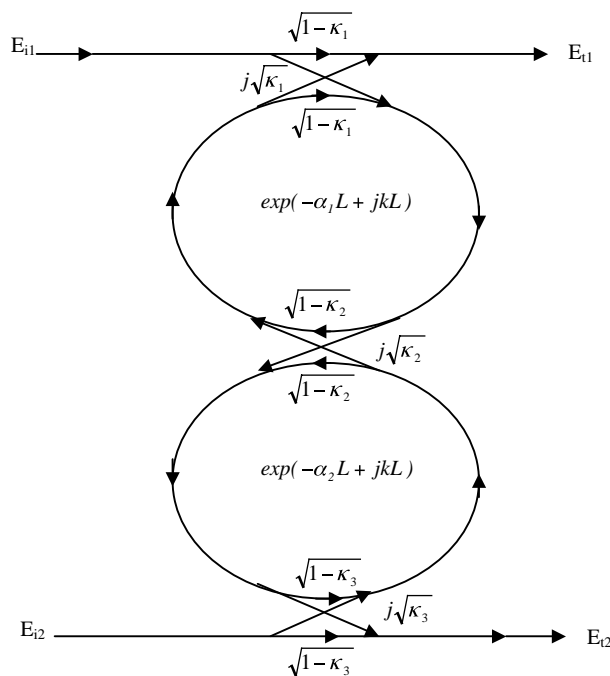


Fig. 1. Simulation model for a DRR.

length. The effective index has been calculated using standard beam propagation method (BPM). In order to include the wavelength dependent dispersion, we have used the model for determining the refractive index according to Utaka *et al.*<sup>8)</sup> The gradient

$$\frac{dn_{\text{eff}}}{d\lambda} \quad (3)$$

is linear in the wavelength range around  $1.55\ \mu\text{m}$ . The effective index can then be written as:

$$n_{\text{eff}} = n_{\text{gr}} + \lambda \cdot \frac{dn_{\text{eff}}}{d\lambda} \quad (4)$$

where  $n_{\text{gr}}$  is the group index.

The coupling region is defined additionally by the coupling factor  $\kappa$ . The equations describing the electric field coupling

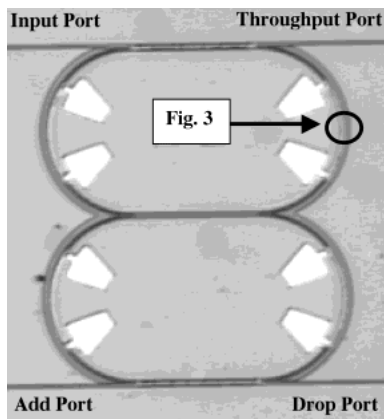


Fig. 2. Photograph of a fabricated DRR.

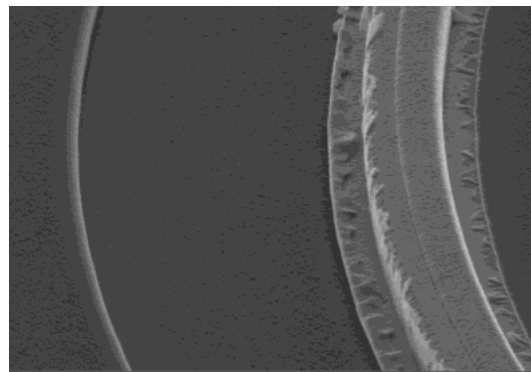


Fig. 3. Waveguide section with Pt-heater.

used for the bar and the cross state are given by:

$$\text{Bar state: } \sqrt{l - \kappa} \tag{5}$$

$$\text{Cross state: } j\sqrt{\kappa} \tag{6}$$

These formulas (1)–(6) describe the entire resonator configuration. The equation for each segment is evaluated and a matrix is obtained for the double ring resonator. Using this matrix it is possible to investigate the influence of variations of the effective refractive index of each segment and obtain the transmission spectrum of the throughput and output ports. This simulation model enables the calculation of the frequency match of a fabricated double ring resonator which will be discussed in section §4.

### 3. Design and Fabrication

The double ring resonator, shown in Fig. 2, was designed for a free spectral range (FSR) of 50 GHz. The device consists of: InP substrate, GaInAsP ( $\lambda_{\text{gap}} = 1.06 \mu\text{m}, 0.38 \mu\text{m}$ ), InP etch stop layer ( $0.020 \mu\text{m}$ ), GaInAsP ( $\lambda_{\text{gap}} = 1.06 \mu\text{m}, 0.84 \mu\text{m}$ ), InP cap ( $0.2 \mu\text{m}$ ). The waveguide design assures both, a monomodal propagation of the light in the waveguide and low bending losses due to a good confinement. Additionally, the waveguide ridge was deeply etched on the outer side of the curved waveguide sections. The waveguide width is  $1.8 \mu\text{m}$ . The ring resonator was structured by standard photolithography and a  $\text{CH}_4/\text{H}_2$  reactive ion etching technique with a  $\text{SiN}_x$  mask, serving also as the mask for the deep etching process. In order to reduce the formation of polymers during dry etching and to minimize the sidewall roughness a small fraction of oxygen was added. The facets of the input and output waveguides can be antireflection coated in order to avoid Fabry-Perot resonances in the straight waveguide section. The Fabry-Perot resonances can be entirely removed as already shown.<sup>2,4)</sup> The double ring resonator (DRR) consisted of two rings with  $R = 200 \mu\text{m}$  which were coupled using two  $-3 \text{ dB}$ -MMIs with a length of  $150 \mu\text{m}$  at the input and output port and a codirectional coupler between the two ring resonators, resulting in a FSR of 50 GHz. The codirectional coupler has a length of  $150 \mu\text{m}$  and a coupler gap of  $1 \mu\text{m}$ . The coupling factor was determined to be 0.06. The pads inside the resonators in Fig. 2 are connected to platinum resistors which are located on top of the waveguide in the curved sections (Fig. 3). The length of each resistor is  $260 \mu\text{m}$  and the resistance is  $100 \Omega$ . The platinum resistors are not only useful

elements to adjust the frequency match in the DRR, but can also be used to adjust the optical length of the resonator to the required operation wavelength.

### 4. Experimental Results

The ring resonator was characterized by using a tapered fiber and by sweeping the wavelength of an external cavity laser. The ring resonator under investigation here is polarization dependent due to waveguide asymmetry. A polarization dependence of the on-off ratio measured for TE and TM of 3 dB was obtained. The measurements reported here have been performed for TE polarization particularly with regard to a future integration with laser components. The characteristic response of the DRR without frequency matching is shown in Fig. 4. The insertion loss was 9 dB (including the coupling losses of approximately 5 dB). The upper curve shows the response from the throughput port and the lower curve that of the drop port. The contrast of the throughput port is 16 dB and that of the drop port 13 dB. The simulated curves reveal a difference of the effective refractive index of about 0.0003, which is also responsible for the different contrast values. According to the calculation, the refractive index is lower in the upper ring. This is mainly due to fabrication tolerances which occur during the deep etching on the outer side of the waveguide in the curvatures.<sup>2)</sup> The length of the resonators is the same. In order to match the resonance fre-

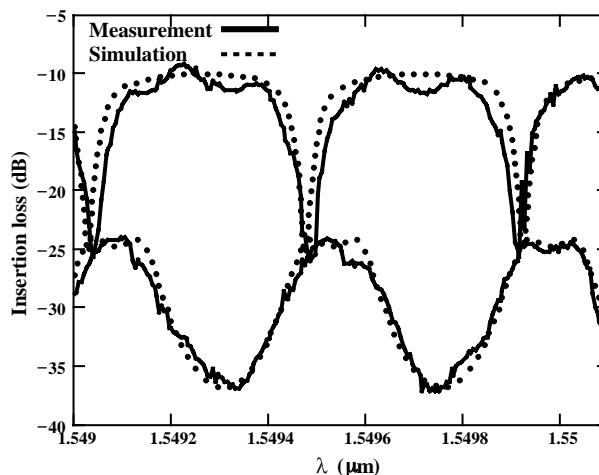


Fig. 4. Filter characteristic of the frequency mismatched DRR.

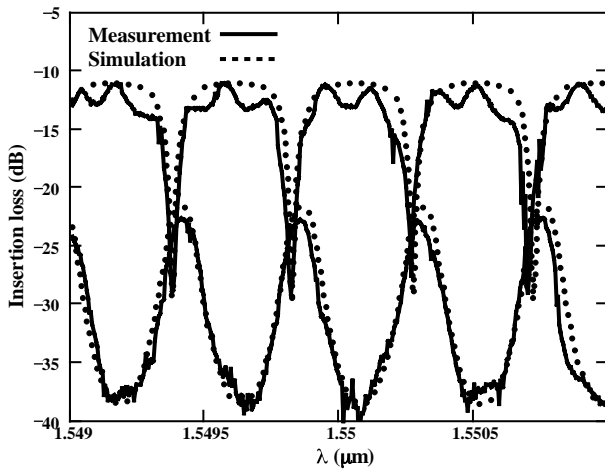


Fig. 5. Filter characteristic of the frequency matched DRR.

quency in both rings in the resonator, the upper Pt-resistors have been used. A voltage of 0.5 V was applied to match the resonance frequency. The result is shown in Fig. 5. The insertion loss was slightly higher (10 dB). The confinement of light in the curvatures rises due to the local heating. This implies an increase in the bending losses, which results in a higher insertion loss. The simulation model predicted a difference in the refractive index between the two rings. As can be seen in Fig. 5, the shape of the transmission characteristic of the drop port has derogated and the on-off ratio of the throughput and of the drop port have increased by about 3 dB, leading to a contrast of more than 18 dB. There is still a small frequency misalignment, which could be eliminated by varying the voltage around 0.5 V in smaller steps (*e.g.* 0.01 V). The temperature coefficient of InP can be approximated in our case to:

$$\frac{dn}{dT} \approx 0.0001 \text{ K}^{-1} \quad (7)$$

The local temperature increased by approximately 3 K. The tuning to a specific wavelength can be performed after the frequency matching in such a way, that both of the Pt-heaters in the two rings come in use. The driving voltage of the Pt-heaters is different in both of the rings due to the previous frequency matching but has to be increased by the same amount in order to shift to the desired wavelength.

### 5. The Triple Ring Resonator with Incorporated SOA Sections

A ring resonator filter is proposed using the simulation tool and experimental results described in §2 and 4. The model for the calculations is shown in Fig. 6. The filter is designed to have a FSR of 100 GHz. The semiconductor optical amplifier (SOA) sections compensate the ring losses to obtain a lossless filter. A single ring resonator with integrated gain section was already demonstrated.<sup>4)</sup> A calculated transmission characteristic is shown in Fig. 7. The coupling losses are not included in the calculation. The four couplers are assumed to have coupling factors of 0.7, 0.2, 0.2, 0.7 from top to bottom, respectively. The full width at half maximum (FWHM) for the throughput and drop port is more than 20 GHz and the on-off ratio is 30 dB for the two ports. This triple ring resonator filter is an excellent candidate to be used as interleaver

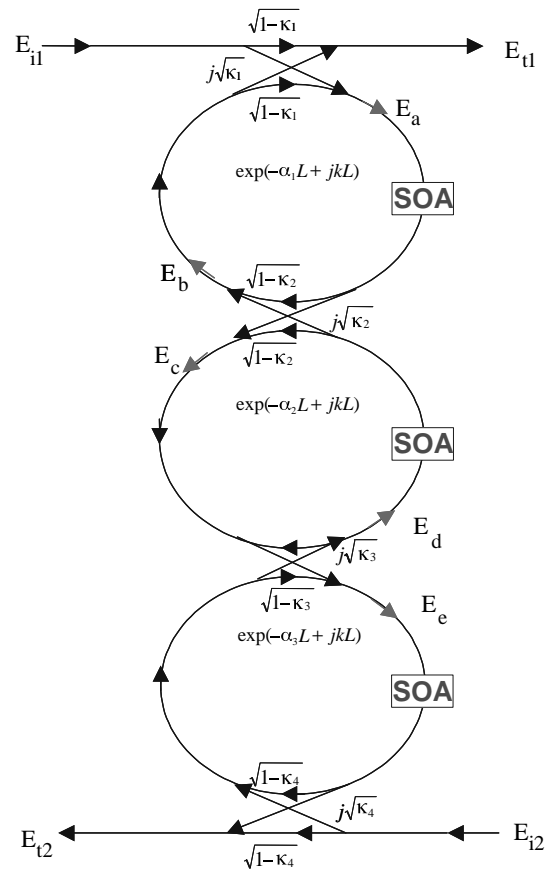


Fig. 6. Simulation model for a TRR.

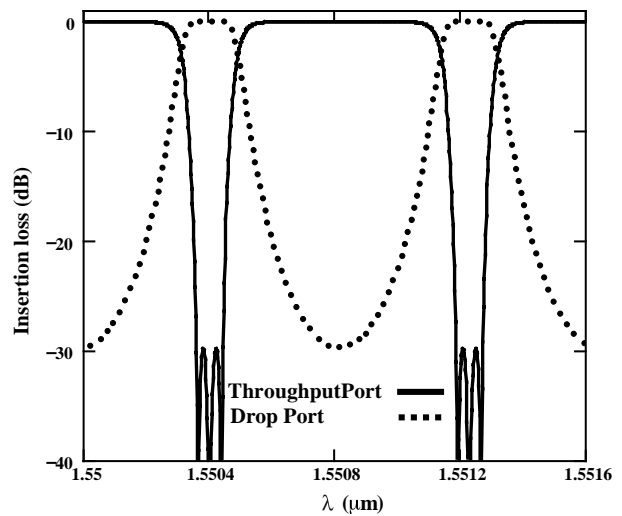


Fig. 7. Filter characteristic of the TRR.

in DWDM systems for the spatial separation of the DWDM channels into two complementary sets at twice the original channel spacing. (*e.g.*: an incoming spectrum with a channel spacing of 50 GHz is transferred into two sets having a channel spacing of 100 GHz.)

### 6. Conclusion

In conclusion, a passive double ring resonator with a free spectral range of 50 GHz was fabricated and characterized. A

simulation model was developed to describe the DRR. Using this model it was possible to qualify a frequency match within the resonator. The difference in the effective refractive index was derived to be 0.0003. The frequency was matched using integrated Pt-heaters leading to an on-off ratio of more than 18 dB for the throughput and drop port. The simulated results coincide very well with the experimental data. We have demonstrated that the Pt-heaters are a very effective tool to match the frequency in the resonator, and to tune the device to a specific wavelength. A model for a triple ring resonator (TRR) filter with integrated SOA sections to compensate the ring losses was developed using the experimental results. The designed TRR has a FSR of 100 GHz and a contrast of 30 dB for the throughput and drop port. By varying the gain (loss), the coupling factor, the optical length and using multiple coupled resonators, tailored passband characteristics can be realized.

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