High-Q Channel-Dropping Filters Using Ring Resonators With Integrated SOAs

D. G. Rabus, M. Hamacher, U. Troppenz, and H. Heidrich

***Abstract*—The filter response of single-ring resonators with integrated semiconductor optical amplifiers based on GaInAsP–InP is presented. The devices with free spectral ranges of 25 and 50 GHz have the form of a racetrack. An on–off ratio of 20 dB, a full-width at half-maximum of 12 and 24 pm, a finesse of 17, and a Q factor of 130 000 and 65 000, respectively, have been achieved. The tuning to a specific wavelength is performed by using integrated Pt-resistors.**

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

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 are of great interest due to their compactness and high-wavelength selectivity [1], [2]. Closer channel spacing (e.g., 50 and 25 GHz) requires sharper filter responses and on–off ratios of more than 20 dB to separate the channels without introducing crosstalk from the other channels.

In this letter, we report the realization of loss compensated, tunable, and switchable ring resonators for use as DWDM channel dropping filters.

II. DESIGN AND FABRICATION

The performance of passive ring resonators for filter applications is limited by internal losses. Therefore, a semiconductor optical amplifier (SOA) which is butt-coupled to the passive waveguide, has been implemented in the single-ring resonator (SRR) (Fig. 1). The SOA length has been designed to compensate the butt-coupling losses and the ring losses. The theoretical butt-coupling losses are below 1 dB (experiment: $\sim$ 2.5 dB/interface). A standard ridge waveguide laser structure was used for the SOA section, which required an additional epitaxial growth step. The layer sequence of the SOA structure is shown in Fig. 2. The quantum wells (QWs) have a bandgap wavelength of $\lambda_{\text{gap}} = 1.55$ μm. The barrier layers are made of n-GaInAsP with a bandgap wavelength of $\lambda_{\text{gap}} = 1.29$ μm. The width of the SOA is 2.2 μm. The structure of the passive waveguide is shown in Fig. 3. The bandgap wavelength of the quaternary material is $\lambda_{\text{gap}} = 1.06$ μm. The waveguide ridge was deeply etched on the outer side of the waveguide in the curvatures for index enhancement [3]. The waveguide width is 1.8 μm. The waveguide design assures both a monomodal propagation of the light in the waveguide and low bending losses.

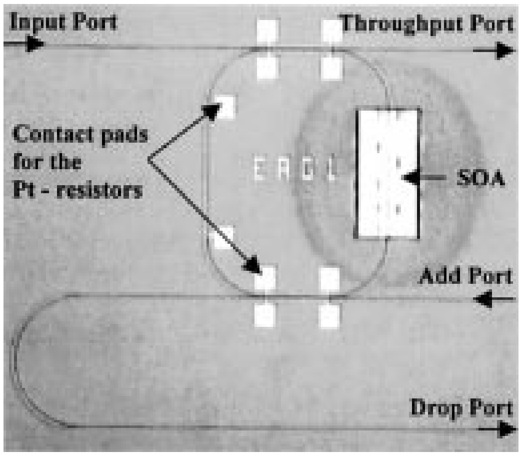

Fig. 1. Photograph of a ring resonator with integrated SOA.

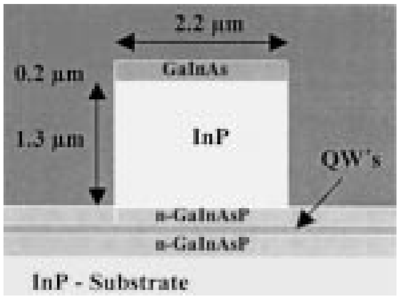

Fig. 2. Layer structure of the integrated SOA.

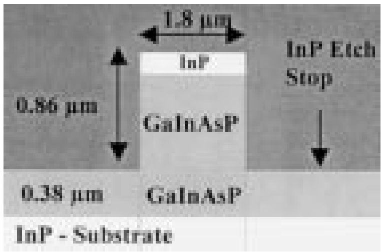

Fig. 3. Layer structure of the passive straight waveguide.

The facets of the input and output waveguides have been antireflection coated.

The SRRs include two codirectional couplers with a coupler gap of 0.9 μm. The power coupling factors are designed to be

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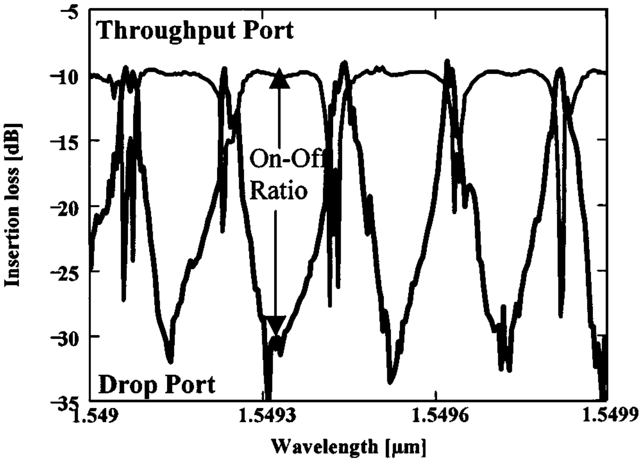

Fig. 4. Experimental result for the ring resonator with an FSR of 25 GHz and an on–off ratio of more than 20 dB.

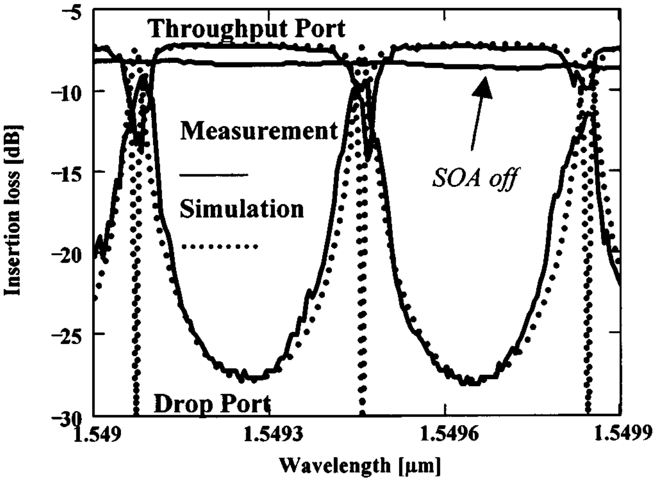

Fig. 5. Results from the experiment and simulation for the ring resonator with an FSR of 50 GHz and an on–off ratio of more than 20 dB.

< 0.2 to achieve an on–off ratio of > 20 dB in the lossless case. The on–off ratio is the relation of the intensity of the throughput port off resonance to the intensity of the drop port off resonance and is given by :

$$\frac{T_{\max-\mathrm{ThroughputPort}}}{T_{\min-\mathrm{DropPort}}} = \frac{(y_1 + y_2 x)^2}{(1 - y_1^2) \cdot (1 - y_2^2) x} \tag{1}$$

with

$$\begin{aligned} x &= \exp\left(-\frac{\alpha}{2} L\right) \\ y_1 &= \sqrt{1 - \kappa_1} \\ y_2 &= \sqrt{1 - \kappa_2} \end{aligned} \tag{2}$$

where $\kappa_{1,2}$ are the power coupling factors of the upper and lower coupler, L is the circumference of the resonator, and α is the intensity attenuation coefficient.

An important figure of merit for the characterization of ring resonators is the Q factor, which is given by [4]

$$Q = \frac{f_0}{\delta f} = \frac{\lambda_0}{\delta \lambda} \tag{3}$$

where f_0 is the absolute frequency and λ_0 is the used wavelength. The shape and the full-width at half maximum (FWHM: δf or $\delta\lambda$) of the filter response is determined by the Q factor. The Q factor in our case is given solely by the geometry of the SRRs, as they are entirely loss compensated by the SOA. This opens the possibility of designing a ring resonator with a specific Q factor.

III. RESULTS

A. SRR With an FSR of 25 GHz

The transmission characteristic of a loss-compensated SRR with a radius of 363 μm and a gain length of 400 μm is shown in Fig. 4. The filter response was measured by coupling the TE polarized signal of an external cavity laser (ECL) via a tapered fiber to the device under test and sweeping the ECL wavelength. The free spectral range (FSR) is 25 GHz. The throughput port power for a fully loss-compensated ring resonator having two identical couplers ($y_1 = y_2$) is zero at resonance. Therefore, a high contrast ratio would be expected in the throughput port filter response. In our case, it could not be detected due to the limited resolution of the used ECL. 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. The on-chip loss for this SRR is taken from the measurement to be 0 dB. The SOA was operated at a current of 90 mA. The coupler length is 200 μm, which results in a power coupling factor of 0.17 for both couplers. The on–off ratio is measured to be more than 20 dB as was predicted by the simulation (1). The FWHM is measured to be $\approx$ 12 pm. The finesse is determined to be 17. The Q factor is evaluated to be $\approx$ 130 000.

B. SRR With an FSR of 50 GHz

The filter characteristic of an SRR with an FSR of 50 GHz is shown in Fig. 5. The radius is 125 μm, the gain length 300 μm, and the coupler length 175 μm. The coupling factor is determined from the simulation to be 0.17. The on–off ratio is as was expected more than 20 dB. The measurement is performed by operating the SOA at a current of 70 and 0 mA. The higher insertion loss obtained from the measurement operating the SOA at 0 mA is due to the coupling factor, neglecting the losses resulting from the straight waveguide and the coupler losses. The SOA absorbs the light coupled into the ring resonator, which is visible in the transmission spectrum of the throughput port. Due to the coupling factor of 0.17 only 83% (-0.8 dB) of the inserted intensity is transmitted and detected at the output port when the SOA is operated at 0 mA. The FWHM is taken from the measurement to be 24 pm.

The finesse is again 17 due to the fully loss-compensated ring resonator resulting in a Q factor of $\approx$ 65 000. The simulation predicts a better extinction than the measurement which is due to the limited resolution of the ECL. The very sharp filter response of the throughput port would be detected if the resolution of the ECL is below 1 pm. As shown recently, the Lorentzian spectrum response of a SRR can be modified to a "box-like" filter

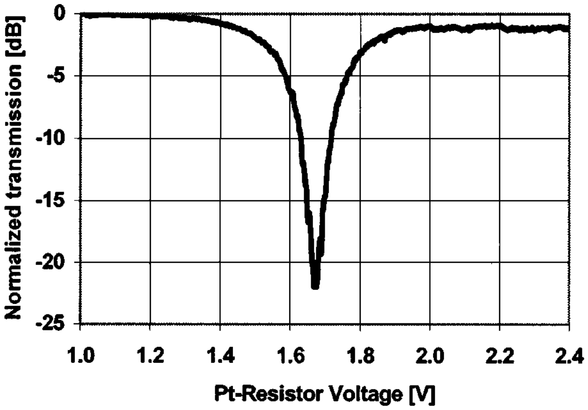

Fig. 6. Measured tuneability of an SRR to a specific wavelength.

response with a flat passband and wider stopband by the use of cascaded ring resonators [5]. The FSR can be increased in multiple coupled ring resonators owing to the vernier effect [6], [7].

Concerning the device feature in the time domain, the filter's system performance depends on the cavity response time of the resonator and the switching speed of the SOA. The application of our devices in high bitrate systems is mainly limited by the time required to charge/deplete the ring cavity. The respective response time scales with the roundtrip time and is increased by lowering the power coupling factor κ. The realized filters presented in this letter are estimated to meet the requirements for DWDM communication systems with a channel spacing of 25 and 50 GHz up to 2.5 Gb/s. So far, the response is characterized in the wavelength domain. System experiments including dispersion measurements will be performed in a following step.

C. Tuneability of the SRR Using Pt-Resistors

Tuneability is essential for the system application of optical filters. In the case of periodic filters, in our case ring resonators, it is important to fit the transmission curve to the defined channel spacing (e.g., ITU-grid). The tuneability is realized by temperature increase with the help of integrated Pt-resistors on top of a part of a waveguide. The Pt-resistors have two functions. The first function is the tuning to a specific wavelength which is demonstrated in this letter, the second function is the resonance matching of multiple coupled ring resonators [8].

The experimental result in Fig. 6 shows the tuning to a specific wavelength. The output intensity is normalized to the insertion loss excluding fiber-chip coupling losses. By detection of the response of the throughput port the voltage is continuously increased. At a voltage of 1.65 V, the signal is "dropped" below -20 dB transmission, which demonstrates that the high extinction from the throughput port predicted by the simulation is detected. The Pt-resistors assure the tuneability over the whole FSR for both the 25 and 50 GHz devices and enable the realization of a wavelength selectable router.

IV. CONCLUSION

In this letter, we have presented single-ring resonator channel-dropping filters with integrated semiconductor optical amplifiers. We have reported preliminary experimental results which show the feasibility of realizing this new class of integrated optical devices. The fabricated ring resonators have free spectral ranges of 25 and 50 GHz, a FWHM of 12 and 24 pm, a finesse of 17, and Q factors of 130 000 and 65 000, respectively. It was demonstrated that the tuning to a specific wavelength can be achieved by using the integrated Pt-resistors. As the Q factor for loss-compensated ring resonators is only dependent on the ring architecture, it is possible to engineer devices with specific Q factors. We believe that ring resonators will cover wide areas of applications in optical communications and signal processing.

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