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Wide Dynamic Range of Ring Resonator Channel-Dropping Filters with Integrated SOAs

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Abstract: We present the first complete simulation of the dynamic range and noise of InGaAsP multi-ring channel-drop filters with internal SOAs. The results show gain saturation, and spontaneous emission noise limit the dynamic range.

OCIS codes: (250.5980) Semiconductor optical amplifiers; (250.3140) Integrated optoelectronic circuits; (230.7408) Wavelength filtering devices

1. Introduction

This paper presents the first complete simulation of the dynamic range and noise of active InGaAsP multi-ring cavity RF-optical filters including gain, gain saturation, and spontaneous emission noise of semiconductor optical amplifiers (SOAs) embedded within each ring cavity of the filter. Cascaded ring-type optical filters with a few GHz resonant bandwidth are useful for processing RF signals in the optical domain in applications such as Optical Code Division Multiple Access systems and RF channelizing filters[1]. Passive and bend radiation losses have a profound impact on the filter performance metrics including the cavity Q and transmission loss. In InGaAsP, the free-carrier limit of low waveguide loss is ~ 3.5 dB/cm so that a 3-ring cascade drop filter of 1 GHz linewidth and 40 GHz free-spectral range has a filter transmission loss of 50 dB, making the addition of SOAs an active area of research[2]. The compatibility of InGaAsP SOAs with monolithic integration makes InP-based photonic integrated circuits attractive as a means of fabricating potentially lossless RF-optical drop filters. Since the Q of the filter is highly sensitive to the internal round-trip loss of each ring, adding an SOA of only 0.5 dB gain in each of the three rings can offset the waveguide loss and bring the filter transmission to unity (see Fig. 1). However, gain distortions and spontaneous emission noise within the SOA hamper performance by reducing the filter efficiency at high optical power and creating a broad spectrum noise floor. This work provides valuable insight into the practical utility of active semiconductor ring filters with internal gain elements.

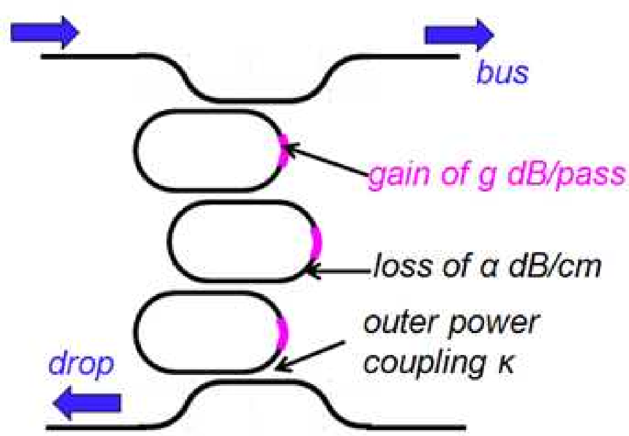

Figure 1: Diagram of channel-drop filter with integrated SOAs.

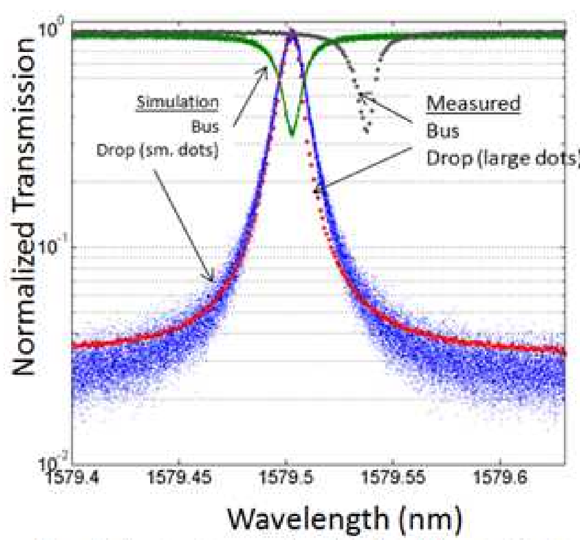

Figure 2: Overlay of measured and simulated characteristic of a single-ring filter with and integrated SOA. Offset of experimental "bus" response is due to temperature drift.

2. Simulations

In order to understand the performance limits of active ring filters and to provide insight into best-design practices for SOAs to be used in filters, we have employed a time-domain travelling-wave model[3] of a 3-ring filter. Within each embedded SOA the model generates local gain and spontaneous emission as a function of injection current and optical power at all wavelengths using the well known time-dependant rate equation method. By computing the local transmission of all considered wavelengths simultaneously at each time-step of the simulation, the time-domain model is capable of simulating local power spectra at any location within any of the rings. The model was first compared to measured filter spectra and spontaneous emission noise of a buried-heterostructure (BH) single-ring filter with 1um wide by 100 um-long SOAs[4]. Figure 2 shows excellent agreement between experimental data from the single-ring active filter and the simulated response. Spontaneous emission noise is seen as the scatter in the simulated results. The noise floor is very close to the measured off-resonance noise-limited filter response. In this simulation the only free parameters were the SOA injection current, and the optical output coupling of the two identical directional couplers. The passive waveguide loss was known from separate measurements of straight waveguides.

Three-ring active filters with directional couplers designed for a nominally 1 GHz, -1.5dB, optical-linewidth and maximally-flat response[1] were then designed and simulated. Passive waveguide loss was set to match the measured loss of 6 dB/cm. Ring radius was set to 200 um for the 1 um wide BH waveguide. Bend loss at this radius was simulated to be less than 0.3 dB/cm. In order to minimize generation of spontaneous emission noise, 3 and 7 centered MQW *pin*-type SOAs with lengths of 20 µm and 15 µm, respectively, were used. Figure 3 shows simulated SOA gain. The 3 QW SOA has 0.6 dB gain per pass while the 7 QW SOA has slightly more than 2 dB gain per pass. Both show gain saturation for greater than 1 mW input power. One important characteristic of active ring filters is that too much gain at the SOA will push the cavity into transparency. This condition is characterized by a rapid increase in output noise and eventually lasing of the ring. The SOA size and gain in our design has been chosen so that the filter transmission is maximized without a significant noise penalty.

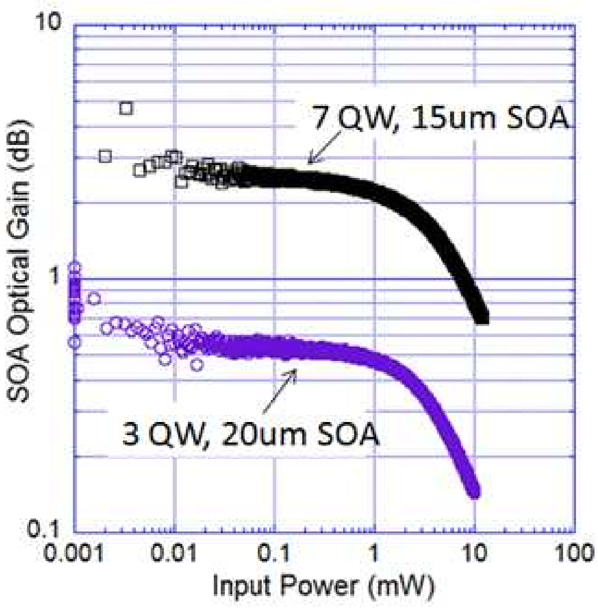

Figure 3: Simulates gain versus input optical power of InGaAsP MQW SOAs. SOAs are 1 um wide of 3 or 7 QW design and 15 or 20 um length as indicated. The 7 QW SOA is driven at 2.25 mA while the 3 QW SOA is driven at 0.5 mA.

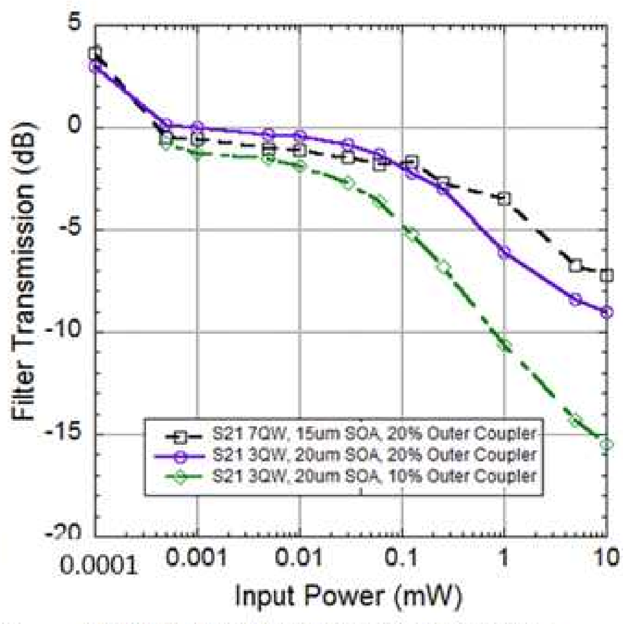

Figure 4: Input to drop-port output filter transmission coefficient, at resonance peak, in dB.

After having established the proper SOA size and injection current for near-zero insertion loss operation of a 3-ring filter at input optical powers of ~10 µW, the input power was scanned from 0.1 µW to 10 mW. The results are shown in Figure 4 for the drop channel. Looking first at the 3QW design with 20% coupling in the outer ring couplers, we see that insertion loss is below 2 dB for all input powers less than 100 μW and that at 1 μW unity gain is achieved. This is a 30 dB dynamic range for loss less than 2 dB. At very low input power the filter exhibits gain due to the increase in SOA gain at the low-power limit. Similarly, at powers greater than 100 μW the insertion loss increases as the SOAs are operating in the gain-saturated regime. For example, at 1 mW input power the power at the entrance of the SOA in the first ring is as high as 6 mW. At such an input power, the SOA gain has dropped from 0.55 dB down to 0.2 dB. When the outer directional coupler is set to 10% power transfer the dynamic range is reduced to 20 dB and the response rolls off more quickly at high power as the reduced ring coupling loss causes higher circulating power in each ring, leading to earlier onset of SOA saturation. Finally, in an effort to improve the dynamic range, a 7-QW SOA injected at 15 kA/cm current density was used. Using the 7QW design the dynamic range increased to ~ 33 dB and the roll-off at high power was reduced.

Using the 7 QW SOA does cause an increase in the noise floor and consequent degradation of the signal-to-noise ratio (SNR) of the filter, as seen in figure 5. Here we see operation of the filter over 5 orders-of-magnitude input power with the SNR increasing monotonically from 3 dB to > 40 dB as the input power rises.

Finally, Figure 6 displays the filter electrical linewidth (defined as the -1.5 dB down full-width of the optical response) showing that the linewidth does not vary significantly with input optical power.

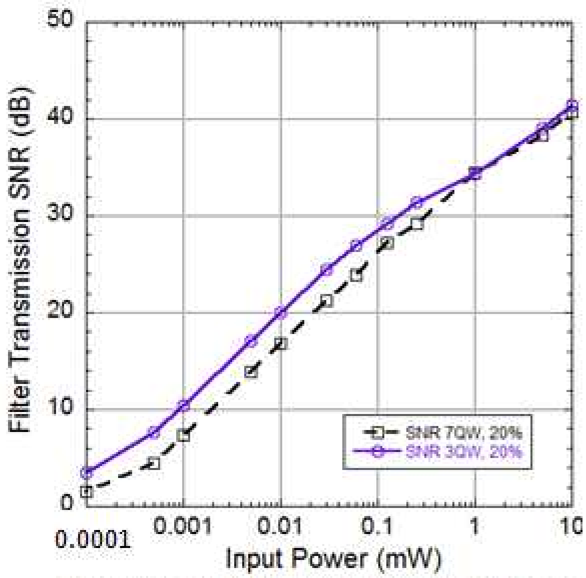

Figure 5: Input to drop-port output filter signal-to-noise ratio, at resonance peak, in dB.

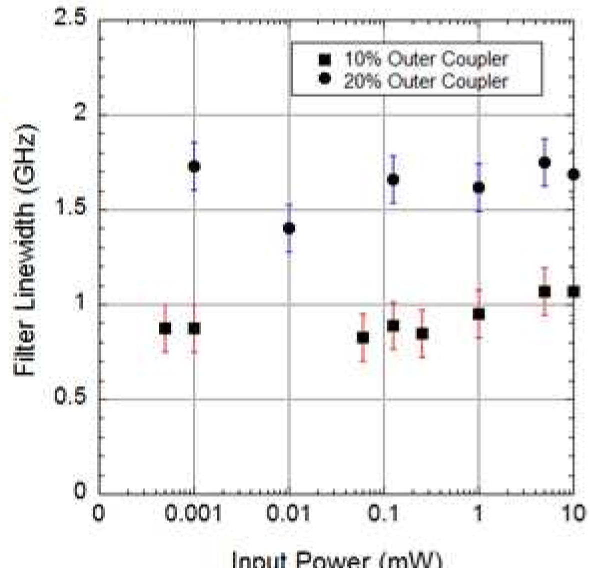

Figure 6: Input to drop-port output filter resonance linewidth as a function of input optical power.

3. Summary

In summary, we have completed a detailed time-domain simulation of multi-ring optical channel drop filters fabricated of InGaAsP BH waveguides with internal SOAs used to offset the passive waveguide loss. Working over 5 orders-of-magnitude variation of the input power it is seen that internal SOAs can provide for > 30 dB dynamic range for < 2 dB drop channel insertion loss for 1.5 GHz linewidth. At the high power regime, SOA gain saturation leads to increased insertion loss. Low power operation is limited by a spontaneous emission noise floor where the SNR drops below 3 dB.

4. References

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