Single Port Optical Switching in Integrated Ring Resonators

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Abstract: We have experimentally investigated single-port injection-triggered switching in a new class of semiconductor ring lasers with integrated gain, phase and passive waveguide sections as a building-block for all-optical signal processing such as high-speed analog-to-digital conversion.

OCIS codes: (250.3140) Integrated optoelectronic circuits; (140.3560) Lasers, ring

1. Introduction

Semiconductor ring lasers (SRLs) are attractive components for all-optical signal processing. They typically lase bidirectional at low drive current and unidirectional at high current due to gain suppression between the competing clockwise (CW) and counter-clockwise (CCW) modes. This unidirectionality can potentially be utilized for bistable operation by switching between the lasing directions. Bistable switching has been demonstrated for various ring designs including circular [1], racetrack [2], and triangular with TIR mirrors [3], and in a variety of laser structures including InGasAs/InGaAlAs/InP [2], GaAs/AlGaAs [4], and InP/AlGaInAs [5]. Current research in the field by Hill et al. has shown switching speeds can be as fast as 20 ps [6], and by Calabretta et al. that switching can be directionally independent [7].

Recently high speed all-optical signal processing designs have been proposed such as a >100 GHz analog-to-digital converter as a milestone for future photonic integrated circuit (PIC) applications [8]. These systems rely on all-optical switching and can gain advantage from monolithically-integrated coupled SRLs for low power consumption, faster operation speeds, and high-order functionality without the need for additional cleaved facets. Such complex structures can benefit greatly from SRLs with phase pads for independent tuning of each laser and tap pads to monitor the power within each coupled SRL during operation. We have evaluated single-port injection triggered switching of SRLs with gain, phase, and tap pads as a building block for all-optical signal processing.

In this paper, we present an initial investigation of the switching mechanism between the CW and CCW modes in a new class of SRLs under injection from a single tunable laser from the same port. We found switching between both lasing directions can be achieved by changing wavelength while using only one port. Such findings are critical for SRL use in integrated photonic devices where much of the prior research on directional switching has been shown for injections into two counter-propagating ports [5,9]. The use of a single switching port greatly simplifies device design by reducing operation complexity with the potential to reduce the device area, the number of components including SRLs, and thus increase speeds for such devices as the >100 GHz all-optical analog-to-digital converter.

2. Material platform and Waveguide Design

The experimental devices integrated active and passive waveguide sections together using an offset quantum-well (OQW) integration platform [10], in the InGaAsP/InP materials system. The common passive waveguide consisted of a 300 nm thick 1.3 µm Q-layer, and the active sections added 7 QWs with a total confinement factor of 7.1% on top of this. Deeply etched waveguides of ~5 µm were used to minimize radiation loss and allow for tight bending radii, although the minimum used was 100 µm. The deep etching was achieved using an ICP RIE system with an Cl_2:H_2:Ar gas mixture to fabricate smooth and vertical sidewalls that are crucial to creating low loss bends. As recommended by Bouchoule et al., it was necessary to place the sample on a Si carrier wafer during the etch to assist in the formation of passivation compounds for smooth sidewalls [11].

The ring has a circumference of 1150 µm with 390 µm active Semiconductor-Optical-Amplifier (SOA) for gain, a 100 µm passive phase adjust pad, and a 100 µm passive tap pad to measure the power inside the ring during lasing. The waveguides are tapered from 3 µm at the SOA for high gain to 1.8 µm at the coupler to allow for shorter 100 µm couplers to be used. Two coupler variations, a 3dB Multimode-Interference (MMI) and a ~6 dB zero-gap directional coupler, are used in the ring designs. An SEM photo of the finished ring with metal p-contacts is shown in Fig. 1 with an MMI coupler. The two coupler designs and their coupling dependence on wavelength are shown in Fig 1b. and Fig 1c. The MMI coupler provides better coupling uniformity across wavelengths while the zero-gap directional coupler varies from 8dB to 5dB cross-coupling.

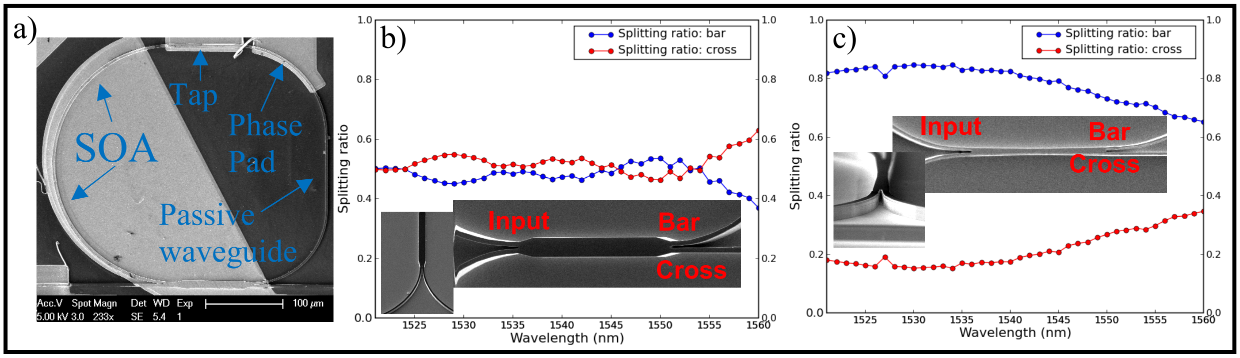

Fig. 1a. SEM of fabricated SRL with MMI coupler, 1b/c. MMI/zero-gap coupler splitting ratio vs. wavelength

3. Switching Results

Inherent bistability in the SRL can be observed as the drive current is increased as shown in Fig. 2. Bidirectional lasing occurs just above threshold, however the SRL becomes unidirectional as the current is increased to 75 mA where the CW mode is dominant and suppresses the CCW mode. At 90 mA this state is reversed and the CCW becomes dominant suppressing the CW up to the peak current at 175 mA. To observe injection triggered switching, the SRL was biased to 160 mA to assure strong suppression between the two modes and high output power levels.

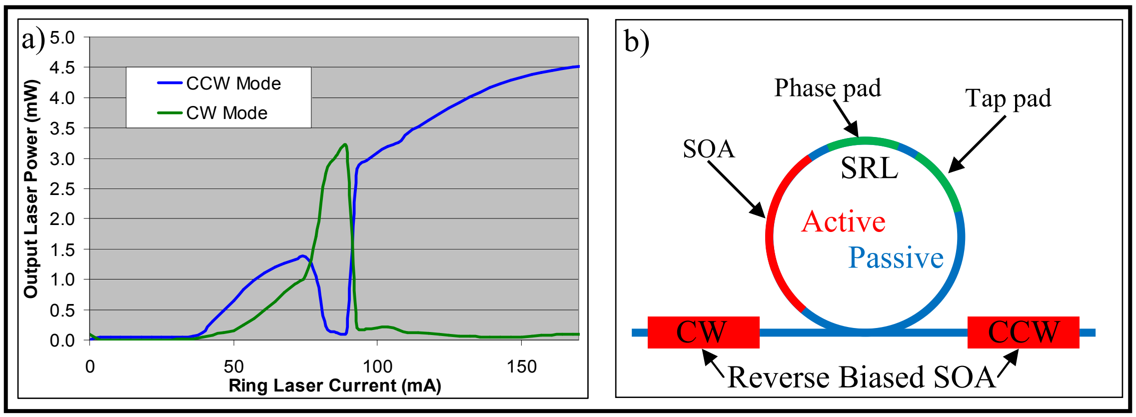

Fig. 2a. Bistable SRL Power vs. Current plot, 2b. Schematic of device

The bistable switching observed for a single injection port is wavelength dependent, while there are several specific wavelengths that can induce switching. The unidirectional ring lasing power inside the cavity with a 3 dB coupler was 9.5 dBm (6.5 dBm on-chip output power) with an injected switching power into the cavity of -25dBm. Low power switching can be achieved with triggering powers ~35dBm less than lasing power. The FSR of the cavity was 0.55 nm at 1.55 µm lasing operation, and a detuning of 0.04 nm between the CW and CCW modes was observed on an optical spectrum analyzer (OSA). Figure 3a shows the output SRL spectrum from a single port when each of the modes is dominant showing an on/off power extinction ratio of 18 dB.

To test the switch's wavelength dependence, the tunable laser was swept in 0.01 nm increments while the two reverse biased SOAs were used to monitor the power in each direction as the ring switched from CW to CCW and then back to CW as shown in Fig. 3b. Switching occurred when the injected tunable laser was 0.01 nm from one of the side peaks of each mode's lasing spectrum. Therefore all potential switches occur at (for integer $n \leq 3$, where $\lambda_{o,CW}$ and $\lambda_{o,CCW}$ are typically detuned by ~0.04 nm):

$$\lambda_{CW\ Switch\,/\,CCW\ Switch} = \lambda_{o,\ CW\,/\,CCW} \pm \left(n \times FSR\right). \qquad (1)$$

However, as shown by Fig. 3b at 1557.15 nm and 1557.85 nm a complete switching does not always occur. The number of complete switching wavelengths was improved by slowing the sweep speed and increasing the injected power. Further improvements to switching may be realized by using a narrow linewidth injection source to maximize the energy coupled into a single mode. Once switched, the stability of the CW and CCW states was verified for over an hour with no external injection. Additionally, for both stable states the lasing mode comb was shifted by 0.3 nm using the phase pads and the temperature changed by ±10^{o} C using a thermo-electric cooler without triggering a switch. Switching results are reported here for operation at 20^{o} C indicating that near-room temperature operation of such devices is possible.

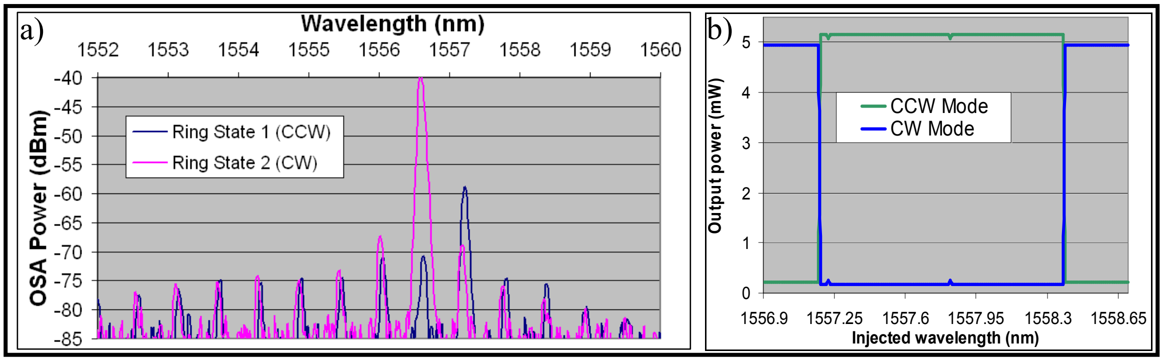

Figure 3a. Lasing spectrum overlay of CW and CCW modes, 3b. Directional switching plot

4. Conclusion

We have characterized single port switching in a new class of SRLs containing gain, phase, and passive waveguide sections for greater control and flexibility in coupled SRL systems. The switching is highly wavelength dependent, in which 0.01 nm matching between the injected wavelength and the SRL lasing peaks is crucial for consistent switching. The required switching power was ~35 dB below the SRL lasing power. This new class of integrated SRL is a promising building-block for all-optical signal processing where each SRL requires independent phase adjustment and optical power monitoring inside the cavity. We have used a fabrication and material platform that is extendable to more complex PICs and these building blocks are fully compatible with other InGaAsP/InP PIC devices. Additionally, their scalability to smaller sizes is mainly coupler limited. Future work might use these building blocks to integrate on-chip tunable sources, detectors, and coupled rings for even greater capability.

5. Acknowledgements

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6. References

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