Hybrid Silicon Ring Laser with Unidirectional Emission

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Abstract: A hybrid silicon ring laser in which the counter-clockwise circulating power is coupled into the clockwise mode is demonstrated. Unidirectional clockwise laser output is achieved with a suppression ratio of 19 dB over the counter-clockwise mode.
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1. Introduction

Ring resonators have become very useful for laser, modulator, and filter devices in silicon (Si) and hybrid Si integrated photonics platforms because their critical dimensions are amenable to today's foundry fabrication processes using photolithography [1, 2]. To generate light with high spectral purity at high optical powers and for optical interconnect applications, ring lasers that support only one sense of optical circulation in the cavity are preferred [3]. However, such unidirectional laser operation typically requires a non-reciprocal loss element in the laser cavity, such as an isolator, which is challenging to integrate into a single chip-scale device.

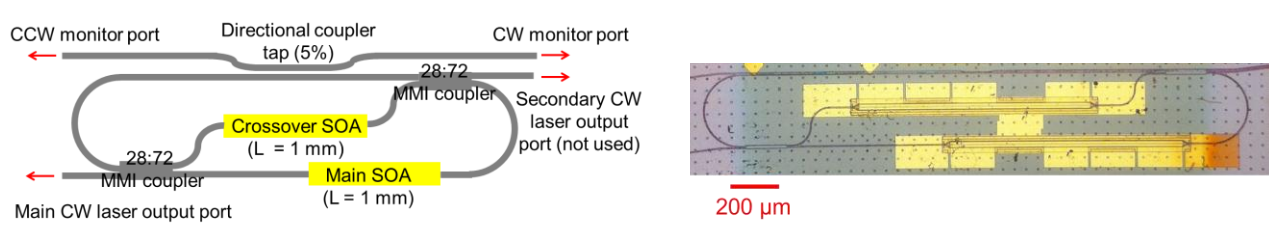
In this work, we present a hybrid III-V-on-Si ring laser capable of unidirectional operation. The design is based on [4], in which an active path in the ring cavity directs a portion of the counter-clockwise (CCW) circulating light into the clockwise (CW) circulating mode to preferentially enable CW laser operation under specific bias conditions. An isolator is not required. Our laser was designed using the standard active and passive building blocks in the UCSB hybrid Si integrated photonics platform. Compared to [3] which used a reflector to couple light from one circulation direction into the other, here, the CW and CCW intracavity powers were directly compared to investigate the unidirectional operation and the coupling of CCW light to the CW mode was tunable.

2. Device Concept

Figure 1(a) shows the schematic of the ring laser design. The directional coupler taps 5% of the CW and CCW intracavity light to allow for the simultaneous monitoring of the amplitudes of the two circulation directions. Unidirectional laser operation is made possible by the S-bend crossover path inserted in the ring laser cavity between the two 28:72 multimode interference (MMI) couplers (i.e., 72% cross-coupled power coefficient). The laser operation is as follows. The CW light remains in the ring resonator path and cannot enter the S-bend, though a fraction is parasitically lost at the top right MMI in Fig. 1(a) to the secondary output port. On the other hand, with each round-trip, a fraction of the CCW circulating light is coupled into the S-bend, where it is amplified before it is injected into the CW direction upon exiting the S-bend. If the phase-shift and amplitude accumulated by the CCW light in the S-bend lead to constructive interference with the CW light in the main ring resonator path, the CW mode would effectively be preferentially amplified relative to the CCW mode, and thus emerge as the dominant laser mode to result in unidirectional laser operation.

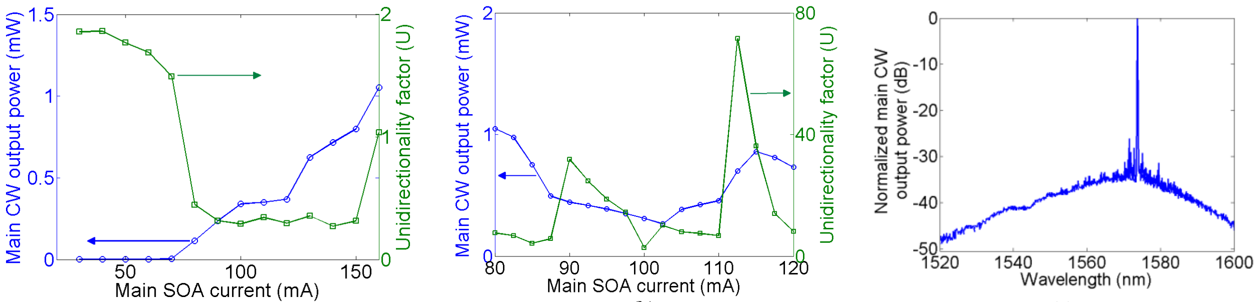
3. Experimental Results

The device was fabricated in the UCSB hybrid Si integrated photonics platform. Si rib waveguides were formed in a silicon-on-insulator (SOI) substrate with a top-Si thickness of 500 nm, a slab height of 250 nm, and a buried oxide thickness of 1 µm. The semiconductor optical amplifier (SOA) sections consisted of cleaved III-V dies that were



(a) (b)

Fig. 1: (a) Schematic of the unidirectional ring laser design. The S-bend inside the ring resonator amplifies a fraction of the CCW light and injects it to the CW direction. The directional coupler tap enables the simultaneous monitoring of the CW and CCW intracavity light. (b) An optical micrograph of the device.



(a) (b) (c)

Fig. 2: The on-chip optical power at the main CW laser output port and the unidirectionality factor ($U = P_{mon,\mathrm{CW}}/P_{mon,\mathrm{CCW}}$) as a function of the current applied to the main SOA at crossover SOA currents of (a) 30 mA and (b) 137.5 mA. At the low crossover SOA current, unidirectional laser operation was not observed. In (b), U reached a maximum of about 72 (≈ 19 dB) at a main SOA current of 112.5 mA. (c) The laser emission spectrum at this maximal value of U showing single-mode operation.

wafer-bonded atop the Si using a low temperature hydrophilic bonding process [5] and defined with reactive ion etching. Pd/Ti/Pd/Au and Pd/Ge/Pd/Au contacts were deposited to form the P and N contacts, respectively. Adiabatic tapers in the Si and III-V levels launch a hybrid mode in the SOA regions [6]. The lengths of the main SOA for the laser and the crossover SOA in the S-bend were 1 mm. For this run, the Si rib waveguide loss was about 8 dB/cm, the loss per taper transition was about 0.8 dB, and the reflection per transition was about -29 dB. The output waveguides of the device were tilted at an angle of 7^{o} relative to the polished facet to reduce reflections. Finally, the facets were coated with a two-layer anti-reflection coating for -33 dB power reflection.

To characterize the laser, we collected the emission from the monitor and main CW laser output ports using tapered single-mode fibers with a nominal spot diameter of 2.5 µm at a wavelength of 1550 nm. We define a metric, the unidirectionality factor, U, as $U = P_{mon,\mathrm{CW}}/P_{mon,\mathrm{CCW}}$, where $P_{mon,\mathrm{CW}}$ and $P_{mon,\mathrm{CCW}}$ are the optical powers at the CW and CCW monitor ports, respectively. We optimized for the fiber-to-chip alignment using the waveguide path between the two monitor ports throughout the measurements. We assumed that the fiber-to-chip coupling losses were identical at the two monitor ports, and by calibrating for the fiber-to-chip coupling loss, we were able to extract the on-chip power. The laser die was mounted on a temperature-controlled stage and measured at 20^{o}C.

Fig. 2(a) shows the on-chip power at the main CW laser output port and U as a function of the main SOA current at a low crossover SOA current of 30 mA. In this regime, the loss in the crossover S-bend path was large. As expected, the laser operated as a typical ring laser; both CW and CCW modes were equally present and U varied between 0.3 and 2. The laser output power was limited to about ~1 mW due to the losses in the cavity, in agreement with design simulations. Fig. 2(b) shows the main laser output power and U for a higher crossover SOA current of 137.5 mA. The unidirectionality factor became significantly higher than that in Fig. 2(a), though the output power and unidirectional operation were sensitive to the current applied to the main SOA, since the phase of the crossover signal was sensitive to the SOA current. The CCW intracavity power was suppressed by up to 72 times relative to the CW power when the current in the main SOA was 112.5 mA. Interestingly, at this maximal value of U, the laser emission appeared to be single-mode (up to the resolution of the optical spectrum analyzer of 0.1nm). The laser output spectrum is shown in Fig. 2(c). This mode selectivity may have been enabled by minute reflections within the cavity as well as the interference condition that would have been required to achieve a high unidirectionality.

4. Conclusion

We have demonstrated the unidirectional operation of a hybrid silicon ring laser with an internal crossover path. A drawback of the design is that the unidirectionality is sensitive to the bias conditions of the main and crossover SOAs due to the interference between the CW light in the main ring path and the CCW light injected from the S-bend. Nonetheless, this design is simple to implement and led to a single-mode emission spectrum. It may open avenues toward other unidirectional hybrid ring laser designs.

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