Regimes of operations of semiconductor ring lasers under optical injection and applications to optical signal processing

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Abstract: We present a detailed characterization of the semiconductor ring-laser operating regimes with special emphasis on the response to optical injection. Applications to an optical set/reset bistable memory and four-wave-mixing tunable THz signals generation are demonstrated.

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All-optical signal processing based on photonic integrated nonlinear devices may provide a viable solution for devising routing functions for high speed optical packet switched network. Monolithic semiconductor ring lasers (SRL) exhibit a variety of operating regions in which highly nonlinear interactions between the clockwise (CW) and counter-clockwise (CCW) propagating modes induced by external optical signal can be exploited for all-optical functions [1-3]. However, besides the works in [1-3], an extended characterization of the SRL behavior under optical injection in each operation regions has not been presented yet. In particular, a detailed spectral analysis of the SRL investigated under 'coherent' (resonant with the lasing mode) and 'incoherent' (resonant with a side mode) optical injection and CW/CCW injection, can reveal novel SRL operation regions and physical insight that can be exploited either for optical signal processing applications and for the development of an accurate model of the SRL. In this paper, we provide a detailed analysis of the SRL under optical injection. We found that the SRL exhibits six operation regions not observed earlier. An optical set/reset bistable memory and four-wave-mixing based tunable wavelength converter and terahertz signal generator are reported. Details reveal an unobserved wavelength detuning between the two bistable modes, and the independence in the directional switch operation from the injection sides.
The experimental setup is shown in fig. 1. The InGaAsP/InP bulk SRL had 2 mm active length, and thus a free-spectral-range (FSR) of 40 GHz. The waveguide's current was kept fixed at 30 mA to guarantee very low ASE noise and feedback due to reflections. The ring threshold was found at 240 mA of current. The tunable lasers were used as external light sources and the optical circulators for diverging the SRL CW and CCW output signals to a high resolution (0.18 pm) OSA, a multi-wavelength meter, and an oscilloscope for spectral and time-domain analyses.

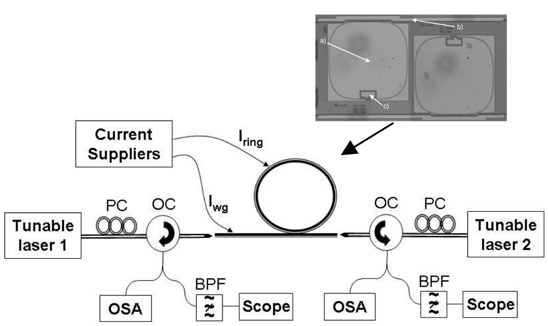

Fig. 1. Experimental set-up for SRL characterization.

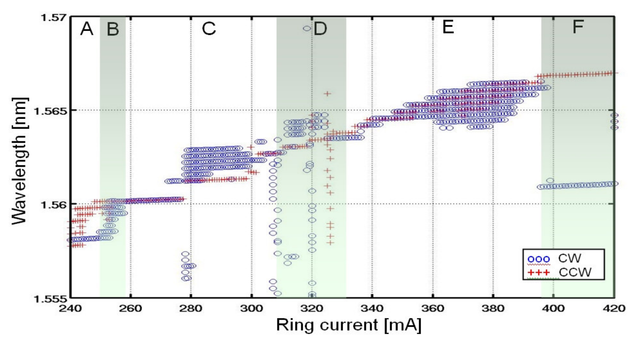

Fig. 2. Wavelength mapping curves versus the ring current.

First, both sides of SRL were connected to a 6GHz-resolution multi-wavelength meter; Fig. 2 shows the wavelength of the optical peaks of the ring for different pumping current. Second, for different pumping currents, optical power was injected from both sides of the ring by the tunable lasers. According to the response of the SRL to optical injection, we identified six different regions of operation, labeled from A to F in fig 2.
Region A - CW Unidirectional single mode operation was observed just above the threshold. The CW and CCW optical spectra without and with injection are shown in fig 3 a-b. The side mode suppression ratio (SMSR) was 15 dB. Under optical injection, the CW mode was suppressed and no directional switching was observed. The linewidth broadening (see inset in fig. 3b) is due to carrier-beatings in the ring. Similar results were obtained for either coherently and incoherently optical injection and whenever injecting from CW/CCW. Once the injection was removed, the original situation resumed. This operation region may be exploited to wavelength convert the data information of an external probe to the one of the SRL CW light.

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Region B – Bidirectional multimode operation. Measured optical spectra of the CW and CCW are very broad and the SMSR was 1 dB. Optical injection induced an unbalance in the power of the two sides, but the SRL remained bidirectional. As in region A, original operation was resumed once the injection was removed.

Region C- Unidirectional single mode with directional bistability. Without optical injection, the SRL presents unidirectional CW lasing operation. The optical spectra are reported in fig. 3c. The SMSR was 25 dB and the counter-propagating modes were at the same wavelength, as shown in the inset. When an optical signal coherent with the lasing mode was injected in the SRL, the SRL exhibits directional bistability lasing in single mode unidirectional in CCW direction, which remained stable once the injection was removed as shown in fig 3d. The directional bistability can be used for devising optical memories. The directional extinction ratio was 25 dB. Although directional bistability controlled by coherent injection has already been presented in [2], we found some novel properties of the SRL which can have practical impacts in devising such optical memory. First, we observed a frequency detuning of 4.625 GHz (0.037 nm) between the two bistable modes (see inset in fig. 3d). This has important and practical implications; the wavelength of the set-signal differs from the wavelength of the reset signal. Indeed, by using the correct wavelength for the set and reset signal, directional switching between the two bistable modes occurs for both coherent and incoherent injection and for both directions of optical injection. This differs from [2] where the switching is reported only when the injection is counter-propagating to the lasing direction. We believe that such detuning arises from a refractive index change induced by the optical power difference between the two lasing modes, and it should be a general feature of any SRL operating in a unidirectional fashion, with directional bistability. We also reported the time domain switching between bistable states as shown in fig. 3e. A switching speed of around 1.5 ns was measured. Faster operation can be obtained by scaling down the dimension of the laser [1]. In fig. 3f the optical transfer function is reported as function of the optical input power. Once reached the threshold (-15.7 dBm), the SRL abruptly switches to the other state.

Region D - Unidirectional with mode hopping between CW and CCW lasing modes. With no injection, the optical spectra are shown in fig. 3g. When a resonant optical signal was injected into the SRL, FWM products are generated as shown in fig. 3h. By exploiting the phase relations in the FWM products, tunable wavelength converter and THz signal generator may be realized. As an example, we report in fig. 3h the FWM products when the optical input signal is tuned to two different mode of the cavity. Removing the injection, the original condition restored.

Region E - Bidirectional multimode. The optical spectra of the two counter-propagating modes are similar to the region B. However, under injection FWM products arise at the CW (CCW) direction if injecting CW (CCW), and then similar applications as in D can be obtained. Moreover, injection locking has been observed in this region.

Region F – Unidirectional multimode. Similar generation of FWM products as in region E, but the original optical spectra show unidirectional operation in both directions at distinct wavelengths spaced of about 6 nm.

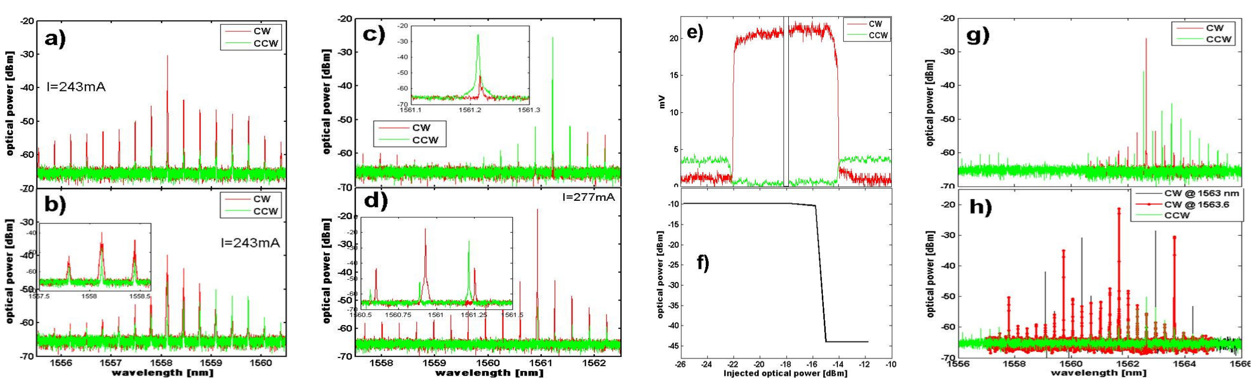

Fig. 3. Optical spectra in the region A, C and D, and time domain switching and optical transfer function of the optical memory in region C.

In conclusion, we presented a detailed characterization of SRL operating regimes with special emphasis on the response to optical injection. Novel operation regions useful for applications in optical signal processing were observed. Experimental evidences on the operation of an optical memory and tunable FWM-based signal processing were presented. Novel details are reported revealing either a wavelength detuning between the two bistable modes that in practice implies the use of detuned wavelengths for the set and reset signal, and the independence in the directional switch operation from the injection sides. Finally, those results can be useful to refine the SRL modeling.

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