Experimental investigation of bistable operation of semiconductor ring lasers under optical injection

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Abstract. *We present detailed characterizations of the bistable operation of a semiconductor ring-laser with emphasis on the response to optical injection. Details revealed that the switching between the two bistable states occurs independently either on the direction and the wavelength of the injected set/reset-signals, while wavelength-detuning of two states was observed.*

Introduction

All-optical bistable memory is one of the crucial components required to realize an ultra-fast packet switched cross-connect node [1]. Monolithic semiconductor ring lasers (SRL) are good candidates to realize an all-optical bistable element due to the nonlinear coupling mechanisms between the clockwise (CW) and counter-clockwise (CCW) propagating modes. Exploiting the nonlinear dynamics, optical memories were demonstrated [2-6]. In [2], two coupled ring lasers where employed to obtain a bistable device which can be externally triggered. Bistability in a single SRL has been demonstrated in [3, 4] by using an external electrical control. The capability to control the SRL by an external optical signal is more attractive than the electronic control because it allows the processing of the signal in all-optical manner without optical-to-electrical conversion stage. A first interesting experimental evidence of directional bistability in a single SRL induced by external optical signal was shown in [5, 6]. For the set (reset) bistable operation, the SRL required an optical control signal injected in the direction opposite to the lasing direction. However, besides those works important details on set/reset switching dynamics and optical spectral analyses of the two unidirectional bistable modes have not been presented yet.

In this paper, we present a detailed characterization of bistability operation in SRL with special emphasis on the response to optical injection. We analyze in detail the effects of the optical power, the direction and the wavelength of the injected set/reset signals on the operation of the optical memory, and we report time domain analyses on the switching between the two states. In contrast with [6], we found out that the directional switching occurs independently of the direction and of the wavelength (at the SRL resonance) of the injected set/reset signals. Those effects have a practical impact in the realization of an optical memory and can be useful to obtain a refined SRL model.

Experimental characterization of the bistable memory

The experimental set-up and the micrograph of the layout of the SRL employed for the investigation of the SRL based optical memory is depicted in Figure 1. The SRL was grown on n-type InP (100) substrates by metal-organic vapor-phase epitaxy (MOVPE). The active region, is a 120 nm thick lattice-matched λ = 1.55 µm bulk InGaAsP layer placed in the center of a 500 nm thick λ = 1.25 µm InGaAsP waveguide core. Bottom and top claddings of the laser structure are 500 nm n-InP buffer and 1.5 μm p-InP with gradual doping levels completed by a 50 nm p-InGaAs contact layer. The ridge waveguides are 2 μm wide. The ring is 2.0 mm long and thus a free-spectral-range (FSR) of 40 GHz. In order to minimize reflections, the bends have a radius of curvature which decreases adiabatically down to 100 μm in order to avoid offsets between straight and curved waveguides. The directional coupler is 200 μm long and the gap is 0.9 μm in width. The reflectivity of the cleaved facets of the output waveguides is reduced by the 7^o angle and anti-reflection coating. The laser has three separate electrical contacts as illustrated in figure 1. The larger contact is used to bias the ring and the directional coupler and it was set to 288 mA. The output waveguide current was set to 30 mA. The temperature of the chip was set to 6.5 degree Celsius. Under those conditions the SRL operates in unidirectional single mode with directional bistability, which allows bistable operation under optical external signals. The CW propagating mode and CCW propagating mode represent state 1 and state 2 of the memory, respectively. In figure 2a the optical spectra recorded with a high resolution (0.18 pm) OSA of the CW and CCW modes is reported when the optical memory is in the initial condition set in state 1. The directional extinction ration (DER) was higher than 35 dB.

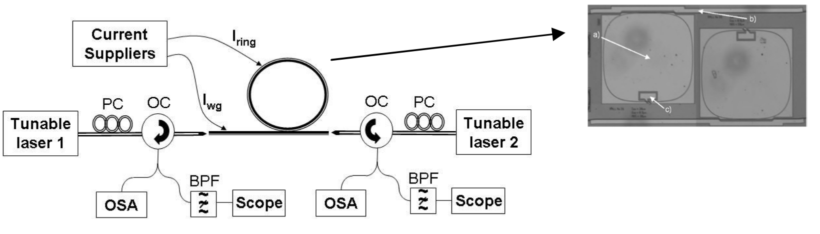

Fig 1. Experimental set-up for SRL characterization. Chip top-view and ohmic contacts are also reported.

First, we investigate the response of the bistable device with respect to the direction of injection of the set/reset signals. The wavelengths of the set and reset signals were 1561 nm and 1561.28 nm, respectively. Starting from the memory set in state 1 as shown in figure 2a, we injected the optical set signal counter-propagating to the CW lasing mode. As a result, the memory commutes to state 2, as reported in figure 2b. The measured DER was higher that 35 dB. We inject the reset signal counter-propagating to the CCW lasing mode to commute the optical memory back to state 1. The optical spectra are shown in figure 2c. Note that between 'state 1' and 'state 2' there is a wavelength difference of 0.037 nm (4.625 GHz). It is worth to mention that if a reset signal at 1561 nm (the wavelength of mode representing state 1) is injected, no switch occurred. The choice of the correct wavelengths for set and reset signals is crucial in the operation of the optical memory. The reason is that the cavity's resonances are slightly different when the SRL operates in CW mode or in CCW mode. Therefore, if the injected signal does not match the cavity resonance no power is coupled in the ring and then no switch occurs. As the cavity resonance depends on the length of the ring and the refractive index, the former is fixed at the fabrication stage and the latter depends on the carrier density of the active material, we ascribe the resonance change to a refractive index change due to a different carrier density resulting by a difference of optical power for the CW and CCW propagation modes. Indeed, around 10 dB of optical power difference between the CW and CCW propagation modes can be observed from figure 2a and 2b.

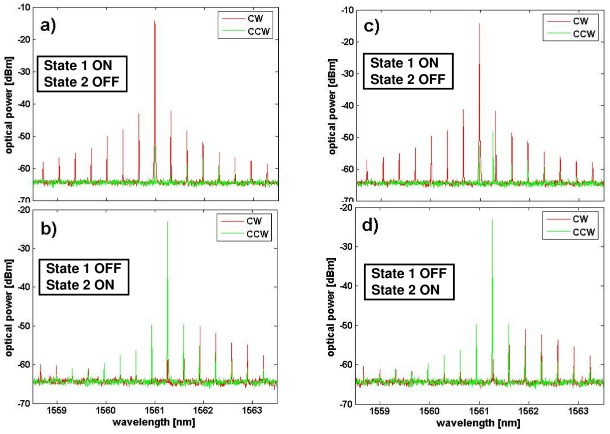

Figure 2. Optical spectra of the CW and CCW modes at different memory states.

Bistable switching has been performed by injecting the set/reset signals in the counter-propagation direction with respect to the lasing mode. To show that the switching can occur independently of the injection direction, we performed the switching by injecting the set/reset signal in co-propagating direction with respect to the lasing mode. Figure 2d shows the performed switch from 'state 1' to 'state 2' by injecting the set signal co-propagating to the CW lasing mode. Then we applied a reset signal co-propagating to the CCW lasing mode to set back to state 1 (shown in figure 2a). Thus, the results obtained in figure 2 demonstrate that the switching between different states is independent of the injection direction, but it is very important the choice of the wavelength of the set and reset signals. Indeed, by using the correct wavelength for the set and reset signal, directional switching between the two bistable modes occurs independently of the injection direction. However, since those two wavelength differ, no switch occurs if the same wavelength is used for both set and reset operation.

We also investigated the switching operation of the memory with respect to the wavelength of the injecting set/reset signals. We observed that switching from state 1 (figure 3a) to state 2 (figure 3b) can be obtained by injecting a set signal at 1559 nm, while a reverse operation (figure 3c) was obtained by injecting a reset signal at 1563.25 nm. In figure 3d shows the optical spectra after injecting a set signal at 1563.28 nm. Those results thus confirm that the switching can be performed by injecting the set/reset signals at the wavelength matching any of the resonance modes of the SRL, as soon as the wavelength is within the SRL gain bandwidth and at one of the ring resonance.

We also reported measurement of the switching time between the two bistable states. Figure 3e shows the time domain traces of the switching of the memory between the CW and CCW propagating modes. The measurements were recorded using the static set-up shown in figure 1 setting the trigger of the real-time oscilloscope on positive and negative slope events. The measured switching speed was 1.5 ns. Faster operation can be obtained by reducing the dimension of the laser [2]. Moreover, the figure 3e confirms the optical power difference between the CW and CCW propagating modes.

In figure 3f the optical transfer function of the state 1 (state 2) is reported as function of the optical input power of the set (reset) signal. The optical power is to be considered at the chip input after the tapered fiber employed to couple the light into the SRL.

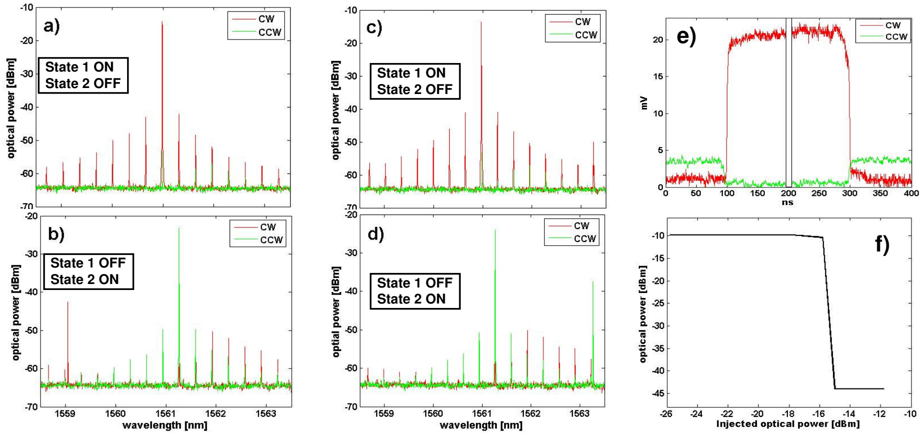

Figure 3. a-d) Optical spectra of the CW and CCW modes for injected signal at different wavelengths. e) Time domain traces showing the switching between bistable states. f) Optical transfer function of state 1 (state 2) as function of the optical input power of the set (reset) signal.

Once reached the threshold (-15.7 dBm), the optical memory abruptly switches to the other state. It is worth to note the extremely low power operation required for switching. This is very important in case of cascading several devices in more complex configuration, such as buffers. Indeed, to drive the next cascaded SRL memory, the output power of the memory should be higher than the required switching power.

Conclusions

We presented a detailed characterization of bistability operation in SRL with special emphasis on the response to optical injection. We analyze in detail the effects of the optical power, the direction and the wavelength of the injected set/reset signals on the operation of the optical memory, and we report time domain analyses on the switching between the two states. We found out that the directional switching occurs independently of the direction and of the wavelength (at the SRL resonance) of the injected set/reset signals. Details also reveal a wavelength detuning between the two bistable modes that in practice implies the use of detuned wavelengths for the set and reset signal. Those results have a practical impact in the realization of an optical memory and can be useful to obtain a refined SRL model.

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