Semiconductor Ring Lasers as Optical Neurons

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Semiconductor Ring Lasers (SRLs) have been shown to have an operation regime in which they are excitable, when the coupling between the counterpropagating modes is asymmetric. In this regime, they fire optical pulses (spikes) as a response to noise perturbations. In this contribution we experimentally and theoretically characterize these spikes and show that their amplitude and width are inversely correlated. We will also show that SRLs can deterministically trigger spikes in each other when they are coupled through a single bus waveguide. This is a first step towards an integrated optical neural network using SRLs as building blocks.

Introduction

Semiconductor ring lasers (SRLs) can generate light in two opposite directions referred to as the clockwise (CW) and the counterclockwise (CCW) mode. We have recently proposed a mechanism for excitability in SRLs, or more generally, in systems with a weakly broken $\mathbb{Z}_2$-symmetry close to a Takens-Bogdanov bifurcation [1]. The convenient device properties of SRLs allow this optical excitable unit to be highly integrable and scalable, potentially allowing for fully integrated optical neural networks and all-optical devices.

In this contribution, we first address the issue that SRLs in the excitable regime show a notable degree of variation in the amplitude and width of the excited pulses [2]. We performed experiments on an InP-based multi-quantum-well SRL with racetrack geometry, fabricated in Glasgow [3, 4]. The optical power is coupled out of the ring cavity by directional coupling to bus waveguides that are integrated on the same optical chip (for further details we refer to Ref. [2]).

Stochastic pulse shape

A typical experimental time series of the CCW mode revealing the excitable behavior of the SRL is shown in Fig. 1(a). The device operates most of the time in the CW unidirectional mode. However, pulses in the CCW direction can be regularly observed. In contrast to what is expected for a typical excitable system, not all excited pulses have the same amplitude and duration. We clearly observe a degree of variation in the amplitude of the pulses. In the same way, a distribution of pulse durations is observed in the experimental time series, and the pulse durations seem to be spread between a minimum of 7 ns and a maximum of 20 ns.

Fig. 1(b) shows a typical experimental pulse shape, and the experimental correlation between pulse amplitude and width is shown in Fig. 2(a). We minimized the noise contributions to the pulse amplitude by performing this measurement without the external SOA.

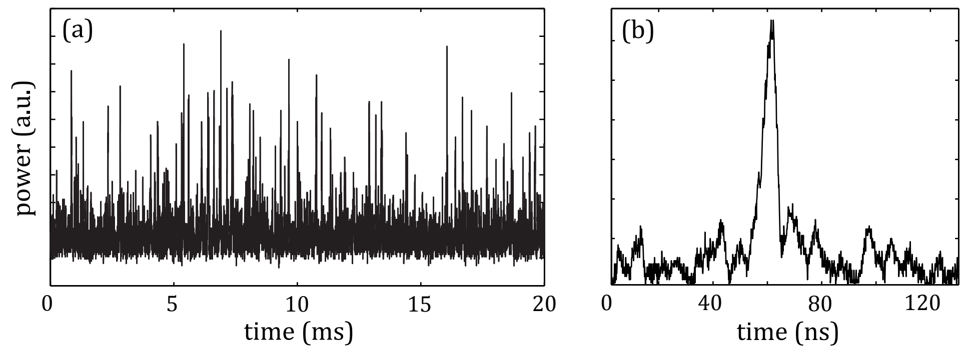

Figure 1: (a) Experimental time series demonstrating the excitable behavior of the SRL operating at a pump current I_p = 47.45 mA ($I_{threshold}$ = 35 mA). The output waveguide is pumped at I_w = 13 mA. An external SOA is used as an optical noise source (I_{SOA} = 700 mA) and coupled in through the output waveguide using a circulator. (b) Typical experimental pulse shape extracted from (a).

The experiments reveal that pulses with a higher peak power are narrower (and vice versa) and that this trend persists for different values of the pump current. Hence, there exists a clear inverse correlation between the pulse amplitude and the pulse duration.

In an asymptotically reduced two-dimensional model for the SRL [5] (valid for time scales slower than the relaxation oscillations) the pulses are a one-parameter family of trajectories that can be parameterized by their initial conditions. This allows for the construction of a curve relating the width and height of the SRL pulses, which is shown as a white line in Fig. 2(b). The correlation between amplitude and width can now be understood due to the different velocity fields at different positions in the reduced phase space. Higher pulses move faster in phase space and are thus narrower, while lower pulses are slower and consequently also wider. The point cloud in Fig. 2(b) is a histogram of pulse width and height from simulations of a standard SRL rate equation model with spontaneous emission noise. It shows that the numerical data cluster around a middle value. For this reason, we argue that the full profile of the amplitude-width curve cannot be experimentally observed in our devices. But the inverse correlation is clearly visible and is the signature of the deterministic evolution of the system once the excitability threshold is crossed.

Deterministic triggering and coupled SRLs

This experimental and theoretical characterization of the pulse shape of SRLs in the excitable regime raises the question if an excited pulse of one SRL could trigger a pulse in another SRL. To investigate this we will address the possibility of using asymmetric SRLs in a coupled configuration [6] (see Fig. 3(a)), which is a first step toward an all-optical neural network using SRLs as building blocks.

In this configuration, we inject a small trigger pulse in SRL A exciting it to emit a pulse which will in its turn trigger a pulse in SRL B. An example of such an event is shown in Fig. 3(b). This occurs for a non-negligible area of coupling parameters (coupling amplitude and phase). For further details we refer to Ref. [6]. Coupled asymmetric SRLs

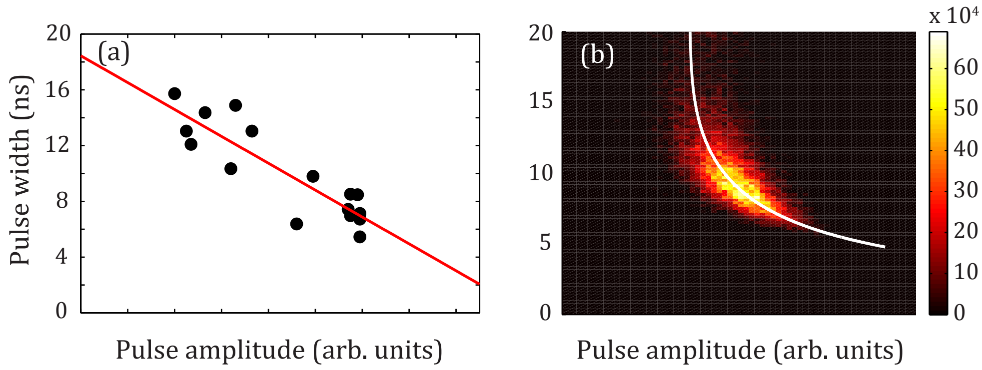

Figure 2: (a) Experimentally measured amplitude and width (FWHM) of excited pulses. I_p= 44.49 mA, I_{SOA} = 0 mA and I_w = 13 mA. A linear fit of the data points is shown by the grey solid line. The correlation coefficient is approximately 0.7. (b) Histogram of pulse width and height from numerical simulations of a SRL rate equation model with noise [2]. The white line indicates the prediction from the deterministic reduced model. θ is a measure for the relative power distribution between the counterpropagating modes [5] ($\theta = 0$: equal power, $\theta = \pi/2$: no power in CW mode, $\theta = -\pi/2$: no power in CCW mode).

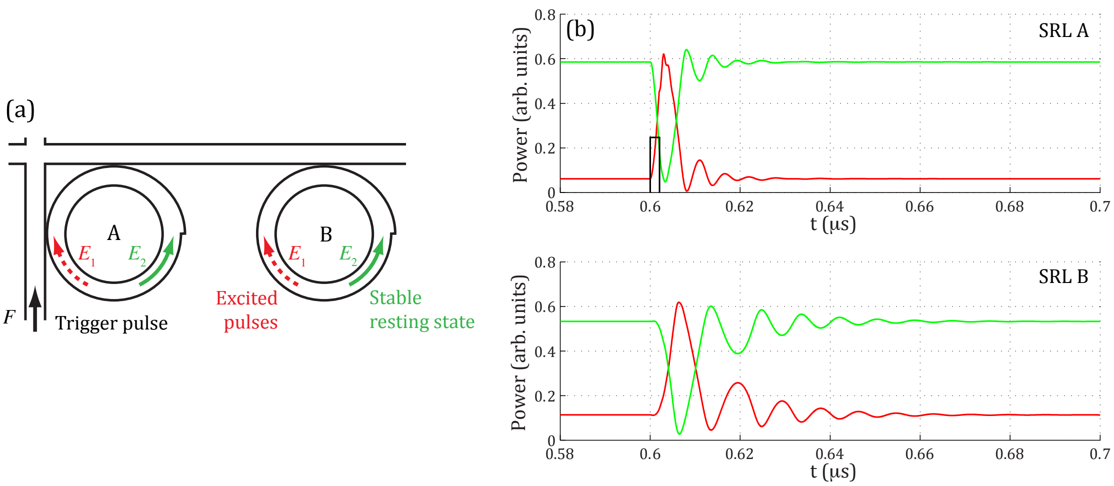

Figure 3: (a) Schematic representation of the considered coupling scheme for excitable (asymmetric) SRLs. The notch to the ring cavity is merely added as a visual indication of the small asymmetry of the cavity. (b) Simulated time traces of rate equations for two coupled SRLs as in (a) [6]. The upper (lower) trace shows the optical powers in SRL A (B). The red (green) line represents the power in the CW (CCW) mode. The black line represents the injected optical trigger pulse, scaled up by a factor of 10^7.

are hence able to excite pulses in each other, mimicking neuron functionality as optical spiking neurons.

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