Optical memory operation of two semiconductor ring lasers coupled by a single waveguide

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We present a numerical analysis of the dynamical behavior of semiconductor ring lasers coupled by a single bus waveguide. Both a weak and strong coupling are considered. Specifically, we show that this coupled system is multistable and can promote instabilities. We relate the internal dynamics in the individual lasers to the field effectively measured at the output of the waveguide. We suggest design constraints leading to coupling phases that avoid instabilities. Finally, we focus on the advantages and disadvantages for optical memory operation of coupled semiconductor ring lasers versus solitary ones.

Introduction

Semiconductor ring lasers (SRLs) are semiconductor lasers where the laser cavity consists of a ring-shaped waveguide. SRLs can generate light in two counterpropagating directions referred to as the clockwise (CW) and the counterclockwise (CCW) mode. Bistability between both directional modes has been demonstrated, allowing to encode digital information in the direction of emission of SRLs [1]. This bistable operation allows SRLs to be used in systems for all-optical switching and as all-optical memories, both in solitary [2, 3, 4] and coupled [1, 5, 6, 7, 8] configurations. Moreover, SRLs are highly integrable and scalable [9], making them ideal candidates for key components in photonic integrated circuits.

One of the seminal works reporting on the potential of SRLs as optical memories is the letter by Hill *et al.* [1]. To demonstrate fast optical flip-flop operation, the authors fabricated two SRLs coupled by a single waveguide, rather than a solitary SRL. Nevertheless, the literature shows that a single SRL can also function perfectly as an all optical memory [4]. This raises the question whether coupling two SRLs to realize a single optical memory has any advantage over using a solitary SRL, taking into account the obvious disadvantage of a doubled footprint and power consumption. In a recent experimental investigation of coupled SRLs, we have demonstrated that coupling between SRLs can destabilize the system by exciting relaxation oscillations, similar to an optically injected laser system [8]. In Ref. [10], we have pursued a more in-depth theoretical investigation of dynamics induced by the coupling. Similar as in [8], we consider the single waveguide coupling configuration as shown in Fig. 1. The coupling provides the system with two extra degrees of freedom, the coupling strength and the physical distance between the SRLs. The latter is taken into account by defining a coupling phase equal to the optical phase difference accumulated when traveling from one SRL to another. However, explicit time delay effects in the coupling (because of the finite traveling time between the lasers) are neglected. More details concerning this modelling and the numerical results can be found in Ref. [10].

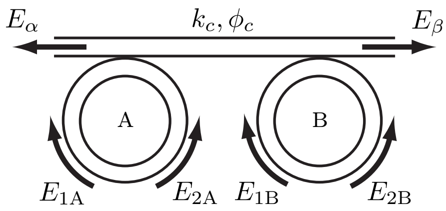

Figure 1: The counterpropagating fields in SRL A (B) are referred to as $E_{1\mathrm{A}}$ and $E_{2\mathrm{A}}$ ($E_{1\mathrm{B}}$ and $E_{2\mathrm{B}}$). The total field at the left (right) output is referred to as E_α (E_β). The coupling amplitude is referred to as k_c, and the coupling phase as ϕ_c.

Model

To model the single waveguide coupled SRLs, we use the rate equation model for a solitary SRL (see e.g. [11, 3]) and modify it to comply with our coupling configuration, as illustrated in Fig. 1. For each SRL X ($\mathrm{X} = \{\mathrm{A},\mathrm{B}\}$), the model consists of two slowly varying complex envelopes of the counterpropagating waves $E_{1\mathrm{X}}$ (CW) and $E_{2\mathrm{X}}$ (CCW) and a third equation for the carrier population inversion N_X:

$$\dot{E}_{1\mathrm{A}} = \kappa\,(1+\mathrm{i}\alpha)\,[g_{1\mathrm{A}}N_\mathrm{A}-1]\,E_{1\mathrm{A}} - ke^{\mathrm{i}\phi_k}E_{2\mathrm{A}} \tag{1a}$$
$$\dot{E}_{2\mathrm{A}} = \kappa\,(1+\mathrm{i}\alpha)\,[g_{2\mathrm{A}}N_\mathrm{A}-1]\,E_{2\mathrm{A}} - ke^{\mathrm{i}\phi_k}E_{1\mathrm{A}} - k_ce^{\mathrm{i}\phi_c}E_{2\mathrm{B}} \tag{1b}$$
$$\dot{E}_{1\mathrm{B}} = \kappa\,(1+\mathrm{i}\alpha)\,[g_{1\mathrm{B}}N_\mathrm{B}-1]\,E_{1\mathrm{B}} - ke^{\mathrm{i}\phi_k}E_{2\mathrm{B}} - k_ce^{\mathrm{i}\phi_c}E_{1\mathrm{A}} \tag{1c}$$
$$\dot{E}_{2\mathrm{B}} = \kappa\,(1+\mathrm{i}\alpha)\,[g_{2\mathrm{B}}N_\mathrm{B}-1]\,E_{2\mathrm{B}} - ke^{\mathrm{i}\phi_k}E_{1\mathrm{B}} \tag{1d}$$
$$\dot{N}_\mathrm{A} = \gamma[\mu - N_\mathrm{A} - g_{1\mathrm{A}}N_\mathrm{A}\,|E_{1\mathrm{A}}|^2 - g_{2\mathrm{A}}N_\mathrm{A}\,|E_{2\mathrm{A}}|^2] \tag{1e}$$
$$\dot{N}_\mathrm{B} = \gamma[\mu - N_\mathrm{B} - g_{1\mathrm{B}}N_\mathrm{B}\,|E_{1\mathrm{B}}|^2 - g_{2\mathrm{B}}N_\mathrm{B}\,|E_{2\mathrm{B}}|^2] \tag{1f}$$

where $g_{1\mathrm{X}} = 1 - s|E_{1\mathrm{X}}|^2 - c|E_{2\mathrm{X}}|^2$ and $g_{2\mathrm{X}} = 1 - s|E_{2\mathrm{X}}|^2 - c|E_{1\mathrm{X}}|^2$. The coupling between the SRLs is modeled by a coupling amplitude k_c and a coupling phase ϕ_c. We assume that the travel time between the SRLs is of the same order as the cavity round trip time, so that we can neglect any effects of a delay time. The two coupling sections to couple the light in and out of each SRL introduce an additional $\pi/2$ phase shift [12]. The light that is coupled from one SRL to the other passes through two such couplers. These two phase-shifts add up to π, which explains the minus sign in front of the coupling term. For simplicity, we use identical parameter values for SRL A and B (for the parameter values see Ref. [10]).

Results

We focus on the asymmetric modes of the system, where both SRLs are either both dominantly lasing in the CW direction (A_{cw}) or in the CCW direction (A_{ccw}). When comparing these states, we noticed that the power levels at the β (α) port are comparable, but that the power levels at the α (β) port are higher for the $\phi_c = \pi/2$ than for the $\phi_c = 0$ case. The underlying reason for this is that the inter-SRL phase

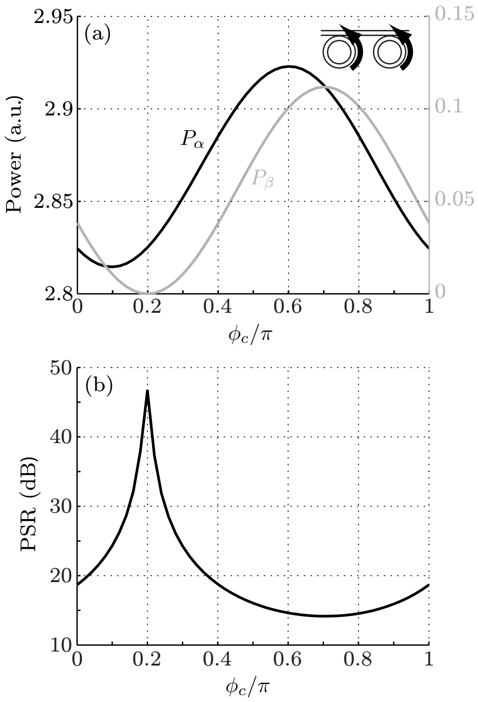

Figure 2: Numerical simulations of Eqs. (1). (a) Steady state power levels at the α-port (left axis, black) and β-port (right axis, red) of the A_{ccw} state as a function of the coupling phase ϕ_c. The minimum value of P_β is 6×10^{-5}. (b) Power suppression ratio (PSR) of the A_{ccw} state as a function of the coupling phase ϕ_c. Parameters values: $k_c = 0.3k$, $\mu = 3$.

difference between the high-power modes remains constant when changing ϕ_c, while the phase difference between the low-power modes changes.
As a result, the relative amount of variation of the power level as a function of ϕ_c is very different at the output ports P_α and P_β. This is illustrated in Fig. 2(a). In this Figure, we have chosen $\mu = 3$. It is clear that while P_α only varies a few percent, P_β ranges from 0.11 to practically zero (6×10^{-5}). This minimum occurs at the point where the phase difference between the low-power modes at the output port, $\chi_1 - \phi_c$, is equal to π, yielding destructive interference (this happens when $\phi_c = 0.2\pi$). Naturally, this causes a sharp peak of 47 dB in the power suppression ratio P_α/P_β, as shown in Fig. 2(b). The solitary SRL has a PSR of 18 dB at $\mu = 3$ (at the same parameter values). So using two coupled SRLs seems to be advantageous from the viewpoint of PSR. However, since we need to bias two SRLs at $\mu = 3$ to achieve the PSR of 47 dB, it is better to compare it with a solitary SRL biased at twice the current $\mu = 6$, which has a PSR of 26 dB. This comparison still shows an improved PSR for the coupled case. Nevertheless, the practical advantage of the higher PSR of single waveguide coupled SRLs (as also reported in Ref. [6]) can be argued since it arises rather due to a decrease of the low-power level, than to an increase in the high power level.

Discussion

In Ref. [10], we have shown that weak coupling can have a stabilizing influence on the SRL operating regimes. If the coupling phase ϕ_c is near zero, oscillatory regimes are completely suppressed in the weakly coupled SRLs, even at parameter ranges where solitary SRLs exhibit alternate oscillations. The power level of the high-power port in the asymmetric states is independent of ϕ_c, but the power level of the low-power port is not. The reason for this is that the high-power modes of each SRL impose a fixed inter-SRL phase relationship very close to $-\pi/2$, whatever the value of ϕ_c. The inter-SRL phase difference between the low power modes is therefore slaved and spans the whole $[0, 2\pi]$ interval for ϕ_c going from 0 to π. The interference of the low-power modes of each SRL will hence be destructive or constructive depending on the value of ϕ_c, yielding different power suppression ratios. More insight into these results concerning a system of coupled SRLs can be found in Ref. [10].

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