Optical injection in semiconductor ring lasers: backfire dynamics

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Abstract: We report on directional mode switching in semiconductor ring lasers through optical injection co-propagating with the lasing mode. The understanding of this novel feature in ring lasers is based on the particular structure of a two-dimensional asymptotic phase space. Our theoretical results are verified numerically and experimentally.

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1. Introduction

Semiconductor Ring Lasers (SRLs) are currently the subject of many experimental and theoretical investigations, ranging from fundamental studies of its nonlinear dynamical behavior to multiple practical applications [1, 2, 3, 4, 5]. In particular, SRLs attract a lot of attention due to their bistability, providing the possibility of operation in either of the two counter-propagating directions. Bistability has been demonstrated [1, 2, 3], and recently exploited for the realisation of all-optical flip-flops [5].

The standard approach to switch the direction of operation of a SRL consists of injecting an optical signal counter-propagating to the lasing mode. Once the signal is removed, the SRL remains stable in this direction [5, 6, 7]. In this work, we propose a scheme based on injection from only one side of the SRL, which would remove the need to have an injection laser at both sides of the SRL in order to switch back and forth between the two directional sides. Recently, we have found experimental evidence of switching induced by co-propagating injection [8]. Such a scheme does not necessarily reduce the switching speed as compared to injection at both sides, nevertheless the possibility of inducing switches from only one side would result in practical advantages, e.g. when designing photonic integrated circuits containing SRLs. In this paper, rather than providing an elaborate bifurcation scenario, we focus on the occurrence and origin of this novel switching method.

From a theoretical point of view, the analysis of directional switching within the existing models [1] is complicated due to the large number of dynamical variables. Therefore, our theoretical analysis is based on an asymptotic reduction to two dimensions of a general rate equation model for a SRL [9]. The switching scheme relies on the special topology of the invariant manifolds of the system. We verify our prediction numerically by simulating a full rate equation model. Finally, the effect is confirmed experimentally.

2. Model

We consider a SRL operating in a single-longitudinal, single-transverse mode. A convenient rate equation model for such a device has been introduced [1, 2]:

\[
\begin{align*}
\dot{E}_{1,2} & = \kappa (1 + i\alpha) \left[ N \left( 1 - s |E_{1,2}|^2 - c |E_{2,1}|^2 \right) - 1 \right] E_{1,2} \\
& \quad - k e^{i\phi} E_{2,1} + \frac{1}{\kappa N} F_{1,2}(t), \\
\dot{N} & = \gamma |\mu - N| \left( 1 - s |E_1|^2 - c |E_2|^2 \right) |E_1|^2 \\
& \quad - N \left( 1 - s |E_2|^2 - c |E_1|^2 \right) |E_2|^2,
\end{align*}
\]

where dot represents differentiation with respect to \( t \), \( E_1 \) and \( E_2 \) are the slowly varying envelopes of the counter-propagating fields, \( N \) is the carrier inversion density, \( \kappa \) is the field decay rate, \( \gamma \) is the carrier decay rate, \( \alpha \) is the linewidth enhancement factor and \( \mu \) is the renormalized injection current with \( \mu \approx 0 \) at transparency and \( \mu \approx 1 \) at lasing threshold. The two counter-propagating modes are considered to saturate both their own and each other’s gain due to e.g. spectral hole burning effects. Self- and cross-saturation effects are added phenomenologically.
and are modeled by \( s \) and \( c \). Contrary to the case of solid-state lasers [10], in the devices under study, the standing-wave pattern has a spatial period much smaller than the carrier diffusion length. Therefore, longitudinal variations of the carrier density will be washed out by the diffusion. As a result, the dynamics of such a carrier grating can be neglected [2, 11, 12]. However, a linear coupling between the two counter-propagating modes does exist. Reflection of the counter-propagating modes occurs where the ring cavity and coupling waveguide meet and can also occur at the end facets of the coupling waveguide. These localized reflections result in a counter-propagating modes occurs where the ring cavity and coupling waveguide meet and can also occur at the end facets of the coupling waveguide. These localized reflections result in a linear coupling between the two fields characterized by an amplitude \( \phi_k \). The term \( F_{1,2}(t) = E_{inj} e^{i\Delta t} \) represents the optically injected field in one of the two modes. \( \tau_{in} \) is the flight time in the ring cavity, \( |E_{inj}|^2 \) the injected power, and \( \Delta \) represents the detuning between both lasers.

3. Asymptotically reduced model

A deeper insight in the switching mechanism can be obtained through an asymptotic simplification of Eqs. (1)-(2) without injection \( (F_{1,2}(t) = 0) \) [9], leading to the following two-dimensional dynamical system:

\[
\begin{align*}
\theta' &= -2\sin \phi_k \sin \psi + 2\cos \phi_k \cos \psi \sin \theta + J \sin \theta \cos \theta, \\
\cos \theta \psi' &= \alpha J \sin \theta \cos \theta + 2\cos \phi_k \sin \psi + 2\sin \phi_k \cos \psi \sin \theta. 
\end{align*}
\]

where \( \theta = 2 \arctan \sqrt{|E_2|^2/|E_1|^2 - \pi/2} \in [-\pi/2, \pi/2] \) represents the relative modal intensity and \( \psi \in [0, 2\pi] \) is the modal phase difference between the counter-propagating modes. The pump current has been rescaled as \( J = \kappa (c - s) (\mu - 1) / k \). Eqs. (3)-(4) are suitable to model the dynamical behavior on time-scales slower than the fast relaxation oscillations. As the phase space of Eqs. (3)-(4) is restricted to two dimensions, it allows for a clear physical picture of the influence of all parameters on the dynamical evolution of the variables in a plane.

Considering the physically meaningful choice of the saturation parameters \( c > s \) and an SRL operating in the bistable unidirectional regime [9], Eqs. (3)-(4) have four stationary solutions: an unstable in-phase (out-of-phase) bidirectional state in \((0,0)\) \([(0,\pi)]\); two symmetric stable states \( CW \) (clockwise) and \( CCW \) (counter-clockwise) at \( \psi \approx \pi \) (\( \psi \approx 0 \)) both corresponding to unidirectional operation, and a saddle point \( S \) in \((0,\pi)\) \([(0,0)]\) which is the unstable out-of-phase (in-phase) bidirectional solution. The stable manifold of \( S \) separates the basins of attractions of \( CW \) and \( CCW \) as depicted in Fig. 1(b). From Fig. 1, it is clear that the basins of attraction of \( CW \) and \( CCW \) fold into each other as the stable manifold of \( S \) spirals inwards.

In Sect. 4, we demonstrate that both the full rate-equation model [Eqs. (1)-(2)] and this reduced system [Eqs. (3)-(4)] are able to adequately describe the directional switching behavior of a SRL on a slow time-scale. We want to stress that, although the two-dimensional phase space picture of the reduced system proves to be very useful in order to gain more insight in the switching process, it is only valid on slower timescales (slow a compared to the relaxation oscillation damping rate. The full rate-equation model, of course, is able to describe the dynamical behavior of a SRL on faster time-scales, including time-scales of the order of the relaxation oscillation period. This being said, the full model [Eqs. (1)-(2)] can only be reduced to the simpler two-dimensional picture in the absence of an optical injection term. Therefore, we numerically simulate the switching processes using the full system with optical injection, and physically interpret the results through a phase space projection in the reduced model from the moment that the injection term is removed. It is important to remark that the phase-space topology of the SRL is common for optical systems, for instance a nonlinear ring resonator.
Fig. 1. Numerical simulations of Eqs. (1)-(2). In (a) the different regimes of operation of the optically injected SRL are indicated in the plane ($\Delta, E_{\text{inj}}$). LS marks the stable locking region in grey, LNS the unstable locking region, and NL the regime without locking. $\Delta$ represents the detuning with the injected master laser, and $E_{\text{inj}}$ the amplitude of the injected signal. (b) shows the phase portrait of the system. CW and CCW are the stable states of the system; $S$ is the saddle. The stable manifold of $S$ is indicated with a black solid line. A and B indicate the equilibrium positions of the system when the counter-propagating (A) or co-propagating (B) signal is injected starting from the CW state. The possible locked states from panel (a) by co-propagating injection are again depicted by the grey region. The external field is injected in the co-propagating direction at $t_{\text{inj}} = 200\,\text{ns}$ and removed at $t_{\text{fin}} = 400\,\text{ns}$. The relaxation trajectories from A-B towards the corresponding equilibrium are marked in grey solid lines. Finally, (c)-(d) depict the time-series for $|E_1|^2$ (grey) and $|E_2|^2$ (black) corresponding to the switches in (b). The injection amplitude and detuning are $(E_{\text{inj}} = 3\times10^{-4}, \Delta = -1.2\,\text{ns}^{-1})$ in (c) and $(E_{\text{inj}} = 6\times10^{-4}, \Delta = -4.2\,\text{ns}^{-1})$ in (d). $\mu = 1.704$ ($J = 0.8$, $k = 0.44\,\text{ns}^{-1}$, $\phi_k = 1.5$, $\kappa = 100\,\text{ns}^{-1}$, $\gamma = 0.2\,\text{ns}^{-1}$, $s = 0.005$, $c = 0.01$, $\alpha = 3.5$).

described by the Ikeda map [14], and more in general for planar dynamical systems which are $Z_2$-invariant [15]. Therefore, we expect the techniques discussed here to be applicable to more dynamical systems than the SRL system investigated here.

4. Optical injection: backfire dynamics

When no external signal is present, the system will relax to either CW or CCW. However, when a signal is injected, the system is shifted away from CW/CCW outside of the asymptotic phase plane. In particular, when injecting a signal strong enough to lock the laser, the relative modal intensity $\theta$ and the modal phase difference $\psi$ will converge to new stationary values. The absolute value of $\theta$ increases due to the change in the suppression ratio of the two modes, whereas $\psi$ changes due to the new phase relation between $E_1$ and $E_2$. When the injected signal is then removed, the system relaxes back to either CW or CCW according to the basins of attraction.

For instance, when the system is prepared in the steady state CW ($\theta < 0$) and one injects a counter-propagating optical field, the relative modal intensity $\theta$ will increase. For a strong
enough signal, this can even rise above the barrier created by the stable manifold of $S$. When the injection is removed, the system finds itself in the basin of attraction of $CCW$ and will relax to it. This is the intuitive switching scenario of a switch induced by a counter-propagating signal.

When injecting a co-propagating signal, the value of $\theta$ is expected to decrease further. Due to the folded shape of the stable manifold of $S$, the system can eventually be driven outside the basin of attraction of $CW$. In this case, when the injection is removed, the system will relax to $CCW$, the counter-propagating stationary operation. This mechanism is counter intuitive as the mode, which receives the least energy from the optical injection, prevails after the injection pulse. In that sense, the laser has “backfired” after the optical injection.

This prediction has been checked by numerical integration of the full set of rate equations [Eqs. (1)-(2)], including $F_{1,2}(t) \neq 0$ to model optical injection. The results are shown in Fig. 1. The system is initially prepared in the state $CW$ at $t_0 = 0$; a counter-propagating or co-propagating signal is injected in the system at $t_{in} = 200$ns and removed at $t_{fin} = 400$ns. The injection amplitude and detuning are $(E_{inj} = 3 \times 10^{-4}, \Delta = -1.2$ns$^{-1})$ and $(E_{inj} = 6 \times 10^{-4}, \Delta = -4.2$ns$^{-1})$, respectively for a counter-propagating injected signal [See Figs. 1(b)-(c)] and for a co-propagating injected signal [See Figs. 1(b)-(d)]. We have chosen these values such that the system can lock to the injected laser field. The locking region (LS), shown in greyscale in Fig. 1(a)-(b), mainly exists for negative values of the detuning $\Delta$, motivating our choice of parameters. This asymmetry in the locking region with respect to the detuning $\Delta$ is typical for semiconductor lasers having a certain linewidth enhancement factor $\alpha$ [16, 17]. Furthermore, we point out that, in Fig. 1(a), $\Delta$ represents the actual detuning of the free running laser frequency with the injected master laser frequency. In fact, the linear coupling term $ke^{i \theta}$ introduces a splitting of the lasing frequency of the SRL into a doublet structure. This frequency shift — for the chosen parameters here $\approx 0.2$ns$^{-1}$ — has been taken into account in Fig. 1(a) by shifting the detuning $\Delta$ used in Eqs. (1)-(2) over $0.2$ns$^{-1}$.

Our simulations show that for $t_{in} < t < t_{fin}$, the system locks to the external signal after an initial transient. The corresponding locked states are indicated as $A$ and $B$ in Fig. 1(b). Both states $A$ and $B$ belong to the basin of attraction of $CCW$. When the injection is removed ($t > 400$ns), the system follows the slow time-scale dynamics of the two-dimensional phase plane. Therefore, it relaxes towards $CCW$ following the stable manifold of $S$. A successful switch to the counter-propagating direction has been achieved in both cases.

Note that in Fig. 1, we have given the system enough time to lock to the injected laser light. Since this process can take several ns, injecting light pulses with a longer pulse duration than this locking time will all have the same effect. On the contrary, we have checked that when shorter injection pulses are used, pulse duration will clearly influence the switching scenario. Since in that case the stationary locking state will not be reached yet, the pulse duration time critically determines the initial point in phase space obtained when removing the optical pulse. Depending on this pulse duration, the SRL will switch its direction of operation or relax back to the same directional lasing mode. The effect of pulse duration on directional switches with resonant injection counter-propagating to the lasing mode has been investigated by T. Pérez et al. in Ref. [7].

Also, we have observed in the numerics that the switching process can become random in the presence of noise. The randomness of the directional switches due to noise is especially large when the injected power and detuning are such that the locking state is close to the stable manifold of the saddle point in the two-dimensional system without injection, shown in Fig. 1(b). As a last remark, we would like to point out that in our numerical simulations in Fig. 1(b)-(d), we have used negatively detuned injection signals. In order to successfully switch the laser through co-propagating injection, the injected intensity has to be large enough. For these in-
projection strengths, due to the presence of the linewidth enhancement factor $\alpha$, the detuning has to be negative in order to have injection locking, as can be seen from Fig. 1(a)-(b). A detailed analysis of the effect of all device parameters lies outside of the scope of this work.

5. Experimental verification

We have performed experiments to confirm the existence of this optical backfire phenomenon. The experimental set-up (similar as in [8]) is shown in Fig. 2(a). The SRL under consideration has a circumference of 2mm corresponding to a Free-Spectral-Range of approximately 40GHz. Its active layer consists of a bulk quaternary layer of InGaAsP providing gain at $\lambda = 1.55 \mu m$. Part of the radiation in the ring cavity is coupled out to a 2mm-long bus waveguide which can be independently contacted. In order to minimize stray reflections, the waveguide crosses the anti-reflection coated facets of the chip under a 7° angle. During this experiment, the current on the waveguide was maintained at 30mA to guarantee low amplified spontaneous emission. Different values of the waveguide current do not change the results qualitatively. The chip is mounted on a copper mount and thermally stabilised at 12°C with an accuracy of 0.01°C. The radiation is collected out of the waveguide by lensed-optical fibres and can be measured with a high resolution optical spectrum analyser or with a sampling scope connected to a fast photodiode. Polarization controllers are used to adjust the polarization of the injected signals while optical circulators separate input and output and prevent from feedback. The external signal is produced by two independent tunable lasers which are fibre-coupled. While varying the bias current on the ring, the threshold is reached at 240 mA. The bias current was scanned until a bistable region was reached between 257 mA and 350 mA. In this region, in absence of external signal, both clockwise and counterclockwise operation are stable. A large side-mode-suppression-ratio (> 25 dB) demonstrates single longitudinal mode operation. During our experiment, we operate the laser in the single-mode bistable region, which is well described by the CW or CCW states in Fig. 1(b). In absence of optical injection, the time traces of the power at output 1 are first monitored for sufficiently long time in order to rule out the possibility
of spontaneous mode hopping. Once the tunable laser is turned on and a resonant signal is injected in the SRL, switches are observed in the time traces of the power of each of the modes and they can be recorded with a triggered oscilloscope.

Typical experimental time traces for the switches are presented in Figs. 2(b)-(e). The signal is injected from input 1, therefore it is co-propagating with the CW direction of the ring and counter-propagating with the CCW direction. We start [Figs.2(b)-(c)] with a CCW operation of the ring. After the injection of the counter-propagating signal, output 1 turns off [Fig.2(b)], while output 2 turns on [Fig.2(c)]. In the second part of the experiment, we consider the ring operating in the clockwise direction and we inject a co-propagating signal [Figs.2(d)-(e)]. After the injection, output 1 turns on [Fig.2(d)] and output 2 turns off [Fig.2(d)]. Therefore the system can be switched between the two directions of operation by both counter-propagating and co-propagating injected signals. Further experiments confirm that the same scenario applies when injecting from input 2 or when injecting resonantly with other than the lasing mode [8]. This behavior is general in the large operating region 257-350 mA.

Finally, we would like to remark that according to our discussion in Sect. 4 a ‘backfire’ requires one to couple a sufficient amount of power into the ring cavity to push the system outside the basin of attraction of the initial mode. However, an experimental characterization of the power dependence of the ‘backfire’ is complicated by the unknown coupling factor between the straight waveguide and the ring cavity and lies beyond the scope of this paper. The switches reported in Figs. 2(b)-(d) have been obtained with an in-fibre injected power of 0dBm, with estimated losses at the fibre-waveguide interface of about 4-5 dB.

6. Conclusions

We have demonstrated that the operation direction of a semiconductor ring laser can be controlled by injecting signal from only one port. Using a topological approach based on a rate-equation reduction, we have predicted the counter-intuitive phenomenon of inducing a switch by injecting a signal which is co-propagating with the field in the ring. The predictions have been verified by both numerical simulations and by experimental measurements on an InP based bulk semiconductor ring laser. To our knowledge, this represents the first theoretical and experimental report of directional switches in a semiconductor ring laser which are induced by co-propagating signals. Such a scheme could provide practical advantages as only one master laser is needed for the switching back and forth. The comparison of the switching speed between co- and counter propagating injection is left for further investigation. We stress that our proposed switching scheme is based on the folding shape of the basins of attraction. Folding basins of attractions are expected for a large class of symmetric systems [15]. A similar switching scheme can therefore be expected to be valid in other systems with similar symmetry such as disk lasers [4, 18]. We finally remark that the topological properties of the manifolds are preserved when scaling down the ring’s size, which suggests that our scheme can be successfully applied for high-speed applications which involve ultra-small rings. We are currently investigating in more detail the switching dynamics, stochastic effects, and the influence of an asymmetry in the device.

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