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# Optical-Injection-Induced Period-One Oscillation in Semiconductor Lasers with Coherent Optical Feedback

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**Abstract:** We show that when a monochromatic optical field is injected into a semiconductor laser subject to external optical feedback, an existing external-cavity mode (ECM) could be converted into another single-frequency mode (called an injection-induced mode or an IIM). The upper boundary of the regime of period-one oscillation is then determined from the Lyapunov-type bifurcation diagrams.

## 1. Description

Consider the configuration of Figure 1. The slave laser diode (SLD) undergoes two external perturbations: a delayed optical field, proportional to  $E(t - \tau)$ , from a distant dielectrical mirror, and a monochromatic optical field from the master laser diode (MLD).

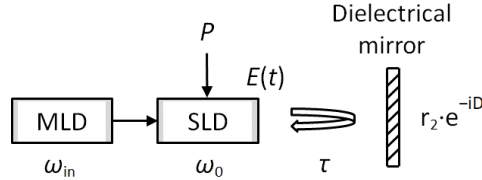


Figure 1. Schematic drawing of the studied system. The output optical field from a master laser diode (MLD) of (angular) frequency  $\omega_{in}$  is injected into a slave laser diode (SLD) whose free-running frequency  $\omega_0$  is close to  $\omega_{in}$ . The external optical feedback is produced by a distant dielectrical mirror of reflection coefficient  $r_2$  and phase  $D$ .  $P$  (dimensionless) is the pump parameter above threshold, which represents the current term.  $\tau$  is the light round-trip time in the external cavity assumed empty.

In the absence of the MLD, this figure is simplified to the classical scheme describing external optical feedback (with  $D = 0$ , see for example [1]). The compound-laser system admits a single-frequency solution called an external-cavity mode or an ECM [2]. Its electrical field is written as  $E_0 e^{i(\Delta - \Delta_0)t/\tau}$ , where the modal amplitude  $E_0$  (dimensionless) is time-invariant ( $E_0 \geq 0$ ),  $\Delta_0$  ( $\Delta_0 = \omega_0 \tau$ ) is the initial feedback phase, and  $\Delta$  ( $\Delta = \omega \tau$ ) is the ECM feedback phase.

When a monochromatic optical field from the MLD is injected into the SLD, the established resonance (if any) of the compound laser will be perturbed and may even be altered. An existing stable (unstable) ECM may become instable (stable). It may also disappear entirely or be converted into another kind of mode with different properties. We are interested in a single-frequency solution in this system. For simplicity, such a solution induced by the injected field is called an injection-induced mode or an IIM. We look for a similar form for an IIM, namely  $A e^{i(\Delta - \Delta_0)t/\tau}$  ( $A > 0$ ). We extend the equations of Lang-Kobayashi [1] by introducing the phase term  $e^{-iD}$  and the injection term  $\omega_1 E_{in} e^{i\Delta \omega t}$  [2] into the rate equation for the electrical field, where  $\omega_1$  (in  $s^{-1}$ ) is the injection rate,  $E_{in}$  (dimensionless) is the amplitude of the injected field, and  $\Delta \omega$  ( $\Delta \omega \equiv \omega_{in} - \omega_0$ ) is the detuning frequency between the injected field and the solitary-laser (SLD) field. We note that in our approach the time parameter  $t$  is in seconds (not normalized).

We show that time-invariant steady-state solutions are possible for both  $\omega$  and the carrier density  $N$  (dimensionless) if and only if  $\omega = \omega_{in}$ . In this case, the injected field «forces» an existing ECM to oscillate with  $\Delta \omega$ . The phase of a possible IIM, which should satisfy the so-called phase condition, determines the adapted value of  $\omega_{in}$ .  $\omega$  and  $N$  are coupled through an additional control parameter denoted as  $\rho$  (in  $s^{-1}$ ;  $\rho = \omega_1 E_{in} A^{-1}$ ). Depending on the characteristics of the SLD, physical solutions of  $A$  ( $A$  should be real and greater than zero.) do exist which are found from the roots of a cubic equation.

To identify if an IIM corresponds to an oscillation with one period, we need to calculate the phase iterates as a function of  $r_2 \{f_{r_2}^n[\Delta(r_2 = 0)]\}$  ( $n = 600$ ) [3] for both of these two mechanisms (without and with the MLD). The upper limit of the regime of period-one oscillation is thus defined at the onset of the period-two oscillation.

An example is given in Figure 2. We take  $r_2 = 0.8 \times 10^{-4}$  as a reference point. The other parameter values are listed in Table 1. It can be shown that at this value of  $r_2$ , there exists an ECM with  $E_0 = 0.0316$  and  $\Delta = -1.175 \text{ rad}$ , and that this ECM is transformed into an IIM with  $A = 0.0021$  and  $\Delta = -2.971 \text{ rad}$  by an injected field with  $E_{in} = 10^{-3}$  ( $\rho = \omega_1 E_{in} A^{-1} = 4.76 \times 10^7 \text{ s}^{-1}$ ) and  $\omega_{in} = \tau^{-1}(-2.971 + 2k\pi) \text{ s}^{-1}$  ( $k = 1, 2, 3, \dots$ ). As shown in this figure, the compound laser operates in the regime of period-one oscillation with both of these two modes.

**Table 1:** Parameters and their values used in Figure 2.

Symbol	Value	Description
$\alpha$	5	linewidth enhancement factor (SLD)
$n_g$	3.4	index of reflection (SLD)
$T_1$	$2 \times 10^{-9} \text{ s}$	carrier life time (SLD)
$\Gamma_0$	$4 \times 10^{11} \text{ s}^{-1}$	inverse photon life time (SLD)
$\zeta$	$2 \times 10^{11} \text{ s}^{-1}$	differential gain (SLD)
$\tau_{in}$	$9 \times 10^{-12} \text{ s}$	internal-cavity round-trip time (SLD)
$\tau$	$1.1 \times 10^{-8} \text{ s}$	external-cavity round-trip time
$P$	$10^{-3}$	pump parameter above threshold (SLD)
$\Delta_0$	$-1 \text{ rad}$	initial feedback phase (SLD)
$E_{in}$	$10^{-3}$	amplitude of injected field (MLD)
$\omega_1$	$10^8 \text{ s}^{-1}$	injection rate (MLD)

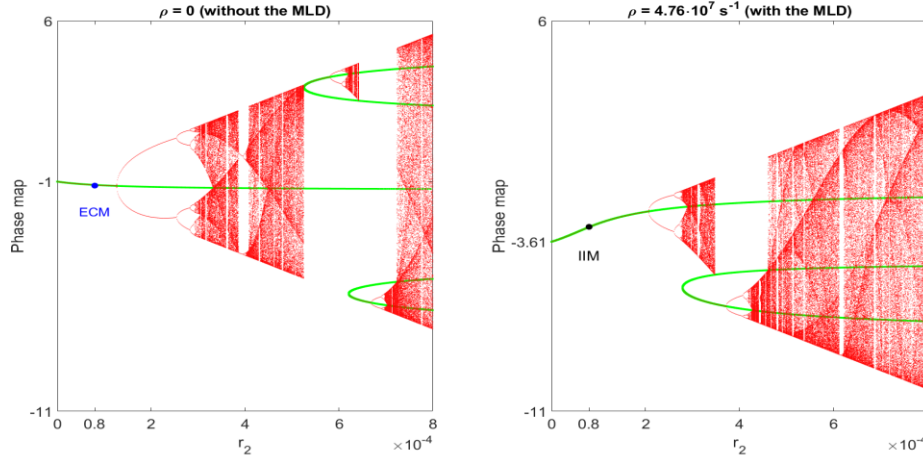


Figure 2. Bifurcation route to chaos of the compound laser. Phase iterates (red dots) with  $D=0$  (All possible stationary solutions, physical or not and dynamically stable or not, should be located on the green curves.). Left: situation of pure optical feedback ( $\rho=0$ ). At  $r_2=0.8 \cdot 10^{-4}$ , an ECM is generated with  $E_0=0.0316$  and  $\Delta=-1.175 \text{ rad}$  (blue dot). The regime of period-one oscillation reaches its upper limit at  $r_2 \approx 1.255 \cdot 10^{-4}$  (onset value corresponding to the first period-doubling bifurcation). Right: situation of optical feedback with optical injection ( $\rho=4.76 \cdot 10^7 \text{ s}^{-1}$ ). When a light beam from the MLD is injected into the SLD with  $\omega_1 \cdot E_{in} = 10^5 \text{ s}^{-1}$ , the compound system transforms this ECM into an IIM with smaller amplitude and shifted phase ( $A=0.0021$  and  $\Delta=-2.971 \text{ rad}$ , black dot). The system has an increased range for the regime of period-one oscillation (upper limit at  $r_2 \approx 2.057 \cdot 10^{-4}$ ).

## 2. Conclusion

Injecting an optical field into a laser diode with external optical feedback transforms, under certain conditions, the already-established ECMs into IIMs. The upper limit of the regime of period-one oscillation, defined at the onset of the period-two oscillation, would be increased if the compound laser operates with IIMs. Further study will include a stability analysis of an IIM as well as an experimental investigation of the considered system.

## 3. References

- [1] R. Lang and K. Kobayashi, "External Optical Feedback Effects on Semiconductor Injection Laser Properties," IEEE Journal of Quantum Electronics, vol. **16**, No. **3**, 347-355 (1980).
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