Experimental study of self-oscillation frequency in a semiconductor laser with optical injection

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Abstract. Period-one and period-two oscillations in a diode laser subject to optical injection are experimentally investigated. The changes in the modulation frequency are studied as a function of the detuning frequency and the injection signal strength.

1. Introduction
Semiconductor lasers with optical injection exhibit very rich dynamics displaying a variety of bifurcations, coexisting attractors, and chaos (see, for example, [1] and references therein). Recently a scheme of two semiconductor lasers in a master-slave configuration has received considerable attention due to its application in optical communication [2]. The periodic exchange of energy between the electrical field and the carrier density results in the characteristic relaxation oscillation resonance in these lasers. The injected signal from the master laser affects the carrier density of the slave laser resulting in a shift of the laser resonance frequency. Normally the relaxation oscillations in an isolated laser is damped, however, the injected signal can excite the relaxation oscillations that leads to undamped oscillations which appear in the Hopf bifurcation.

A number of works have been dedicated to understanding the mechanism of different bifurcations [3, 4, 5, 6] and routes to chaos [1, 7, 8, 9] of the laser system under different operating conditions. At that time both numerical simulations and experiments with the unidirectionally coupled semiconductor lasers have revealed a period-doubling route to chaos [10, 11, 12]. Although a number of theoretical works in this area are relatively large, experimental research remains limited to only few works. Experimental stability diagrams have been obtained [9, 13, 14] showing the regions of different dynamical states of an optically injected GaAs laser as a function of experimentally accessible parameters, normally they are the frequency detuning of the master laser from the slave laser and the injection parameter. The dynamics of a distributed feedback laser was studied recently by Wieczorek \textit{et al.} [15, 16].
The difference (detuning) between optical frequencies of the slave and master lasers results in oscillations of the slave laser power with the beating frequency. The offset of these oscillations occurs in the Hopf bifurcation (HB) and depends on the injected power. At higher injected powers the oscillations undergo the period-doubling bifurcations (PDBs) [1]. Thus, the relation between the oscillation frequency, frequency detuning, and relaxation oscillation frequency is of crucial importance for understanding the mechanisms of the self-oscillations and bifurcations in optically injected semiconductor lasers. Nevertheless, to our knowledge, there are no experimental works devoted to direct measurements of bifurcation diagrams of the oscillation frequency. In this work we present such diagrams and discuss the mechanisms leading to HB and PDB.

This paper is organized as follows, in section 2 we describe the experimental setup and the procedure to obtain the spectra. We show the results in Section 3, and finally we conclude with some discussions in section 4.

2. Experimental Setup

The basic experimental setup is shown in Figure 2. The lasers operate in a master-slave configuration. The diode lasers used are commercially available, with similar wavelengths around 1535 nm, and threshold currents of approximately 8.5 mA for the slave (A38247) and 9.5 mA for the master laser (A37941). The bias current of the slave laser is fixed at 20 mA and the temperature is kept at 20 °C throughout this study, giving as a result the laser emission at the wavelength of approximately 1535.454 nm.

The output of the master laser with polarization direction controlled by a polarizer, is injected via a fiber coupling (using an optical circulator) directly into the slave laser with careful alignment to have good coupling into the laser mode. An isolator is used to make sure that no light was injected into the master laser, avoiding back-reflection light from any component in the setup. The output of the slave laser is coupled into a single-mode fiber, evenly split by an optical fiber coupler, and finally sent to a detection system to measure both optical and power spectra.

Optical spectra is measured by a Michelson-type Optical Spectrum analyzer (Advantest Q8347) with a wavelength resolution of 0.007 nm. Power spectra is obtained by using a photo diode (Discovery Semiconductors DSC20H) to convert the optical signal to an electrical signal, and by displaying the electrical signal on a RF Spectrum Analyzer with a bandwidth of 26.5 GHz (HP E4407B).

The dynamical behavior of the slave laser can be described with respect to two most important control parameters: the injection power and the frequency detuning of the injection field from the free-running frequency of the injected laser (Δ). The master laser wavelength and the injected power are varied by changing the operating temperature and the current of the laser, respectively (see Figures 2 and 3). The operating current and temperature of the master and slave lasers are controlled independently by their controllers.
3. Results
In our experiments the wavelength of the slave laser is always fixed to $\lambda_S = 1535.454$ nm, that corresponds to temperature $T_S = 20$ °C and current $I_S = 20$ mA, while the master laser wavelength $\lambda_M$ is varied using the temperature and current controllers (see Figure 2). We explore the range of the temperatures $T_M$ between 19 °C and 25 °C and the available current range $I_M$ going from 15 mA to 85 mA. It is seen from the figure, the minimum wavelength occurs at $I_M = 30$ mA for all explored temperatures.

![Figure 2](image)

**Figure 2.** Master wavelength versus current for different temperatures at fixed slave laser parameters ($\lambda_S = 1535.454$ nm, $T_S = 20$ °C)

The dependence of the master laser power $P_M = kP_{M,A}$ on the master laser current $I_M$ is shown in Figure 3. Here $P_{M,A}$ is the power measured by the photometer and $k$ is the attenuated factor. The output power $P_M$ is attenuated by a factor of $k = 515 \pm 7$ due to the restrain imposed by the photometer measurement range (below 2 mW). As seen from Figure 3, the first laser threshold occurs at $I_M^{th} = 9.5$ mA and does not depend on the temperature.

![Figure 3](image)

**Figure 3.** Master laser power $P_M$ as a function of current $I_M$. Every line corresponds to fixed master temperature $T_M$.

The dynamics of the slave laser is studied by analyzing both the optical spectrum and the power spectrum. When the optical injection from the master laser into the slave laser diode is increased beyond a weak injection limit for stable injection looking, the output of the slave laser begins to oscillate, i.e. a stable fixed point (cw emission) transforms to a stable limit cycle, that is a signature of HB. We denote the periodic oscillations as a period-1 regime (P1). Increasing the injection strength even more, the period-1 limit cycle undergoes a PDB that can be seen with the signal analyzer. The peak at half of the oscillation frequency appears in the power spectrum. We denote this regime as a period-2 (P2). In this work we are mainly interested in the HB and
the P1 and P2 frequencies as a function of injection power and almost independent on the temperature (Fig. 2), we can construct bifurcation diagrams the corresponding peaks in the power spectrum are too small.

We also leave room for a lost of high-period oscillations in our experiments because the first PDB. However, our system can have also regions in parameter space where higher PDBs take place. We also leave room for a lost of high-period oscillations in our experiments because the corresponding peaks in the power spectrum are too small.

Since the maser laser power (injection power) is determined mainly by the current (Fig. 3) and almost independent on the temperature (Fig. 2), we can construct bifurcation diagrams of the P1 and P2 frequencies as a function of injection power $P_m$. Such diagrams for different detuning frequencies $\Delta = \nu_S - \nu_M$ ($\nu_S$ and $\nu_M$ are the optical frequencies of the slave and master lasers, respectively) are shown in Fig. 4. When $P_m$ is small, the slave laser works in a steady-state regime, i.e. no oscillations are observed. With increasing $P_m$ above some critical value a HB appears in the slave laser at which the laser begins to oscillate at the relaxation oscillation frequency $F_r$ when frequency detuning matches this frequency, i.e. $\Delta \approx F_r$. The small injection power excites resonantly the relaxation oscillations in the slave laser. For our laser $F_r \approx 14$ GHz. A high injection power shifts nonlinearly the resonant laser frequency so that $F$ does not longer coincide with $\Delta$. Simultaneously with the HB the PDB appears in the laser response so that $F/2$ also appears in the power spectrum at $F_r/2 \approx 7$ GHz.

The dependences of the oscillation frequency on the detuning frequency for different $P_m$ are shown in Fig. 5. The lower curve corresponds to the lowest injection power ($I_M = 15$ mA) and the upper curve corresponds to $I_M = 85$ mA. One can see that the minimum oscillation frequency in the period-1 regime $F_{\text{min}} \approx 7.5$ GHz corresponds to $\Delta \approx 10$ GHz. This means that the resonant laser frequency is shifted. As seen from Fig. 5, the diagrams for the period-1 frequency display clear distinguishable minima for each injection power. There exists the low-frequency limit $F_{\text{min}}(\Delta)$ to which all curves approach at large $\Delta$. $F_{\text{min}}(\Delta)$ forms a straight line, i.e. it grows linearly with increasing $\Delta$ but slower than $\Delta$ by a factor of 7. Thus, we may
conclude that at very large positive detuning the oscillation frequency does not depend on the injection power.

![Figure 6. Codimensional-two bifurcation diagram of dynamical regions in space of frequency detuning and injection power. The slave laser parameters are fixed at $I_S = 20\text{ mA}$ and $T_S = 20\text{ °C}$.](image)

The codimensional-two bifurcation diagram showing the ranges of the P1 and P2 oscillations in the parameter space of $P_m$ and $\Delta$ are presented in Fig. 6. The boundaries of the areas of the P1 and P2 regimes are nothing else than the HB and PDB lines. As seen from the figure, a small injection power induces oscillations only in the case of negative detuning. For positive detuning the oscillation threshold is much higher.

4. Conclusions
We have studied experimental dependences of the oscillation frequency of the optically injected semiconductor laser on the injection power and frequency detuning in the ranges of the period-1 and period-2 regimes. First, we have studied the master laser output power and the optical frequency (wavelength) as a function on its temperature and current. Then, we have sampled the spectra of optically injected laser as the injection power was increased. This information allowed us to construct graphs describing the system dynamics.

We have found that the slave laser begins to oscillate at the frequency of its relaxation oscillations equal to 14 GHz when the injection power was increased. The HB appeared as a result of the interaction of the relaxation oscillation frequency with the detuning frequency. The similar effect has been observed for the period-doubling oscillations.

Both the HB and PDB have been found to appear only for negative detuning when the injection power was small. Whereas for the high powers, both bifurcations have been observed for both positive and negative detuning. Moreover, for large positive detuning the oscillation frequency does not depend on the injection power.

We believe that our results can be useful for further understanding of dynamics of optically injected semiconductor lasers.

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