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Electron density dynamics in semiconductor lasers under relatively strong dual optical injection

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In an optically injected semiconductor laser, we theoretically investigate the effect of strong double optical injection on the dynamics of electron density within the secondary locking area and the conventional locking region.

1. Introduction

Semiconductor lasers play an important role in many modern telecommunication applications. In particular, instabilities and chaos in semiconductor lasers have attracted the attention over the last few decades [1]. Semiconductor lasers can show chaotic behaviors in several ways [2] such as the injection of an external optical field [1]. The investigation of chaos in optically injected semiconductor lasers was not only to improve the stability of the lasers but also and more recently to enrich and utilize the nonlinear dynamics and chaotic behaviour [3] in many applications such as cryptography [4]. The major parameter that affects the dynamical behaviour of semiconductor lasers is the linewidth enhancement factor or the so-called alpha factor [5], which relates optical effects to the dynamics of carriers. Therefore more attention should be devoted to reveal the nonlinear dynamics of carrier density in optically injected semiconductor lasers. Even though a few attempts have already been made [6,7], the dynamical behavior of electron density under the injection of two signals is still in need of further investigation [8]. In this paper, we theoretically investigate the dynamics of electron density in semiconductor lasers subject to dual and relatively strong optical injection.

2. Model

The model presented in [6] was extended to include the injection of two optical signals, called master lasers ($ML_{1,2}$). The rate equations for the investigated slave laser (SL) electric field amplitude, phase and carrier density can be expressed, respectively, as follows:

$$\frac{d}{dt}E_0(t) = \frac{1}{2}G_N \Delta N(t) E_0(t) + \eta[E_1 \cos(\Delta t_1) + E_2 \cos(\Delta t_2)] \tag{1}$$

$$\frac{d}{dt}\phi_0(t) = \frac{1}{2}\alpha G_N \Delta N(t) + \eta\left[\frac{E_1}{E_0(t)}\sin(\Delta t_1) + \frac{E_2}{E_0(t)}\sin(\Delta t_2)\right] \tag{2}$$

$$\frac{d}{dt}N(t) = J - \frac{N(t)}{\tau_s} - G_N(N(t) - N_0)E_0^2(t) \tag{3}$$

where $E_0(t)$, E_1 and E_2 are the electric field of the SL and $ML_{1,2}$, respectively, G_N is the material gain coefficient, $\Delta N(t)$ is the population inversion defined as $N - N_{th}$ where N is the carrier density and N_{th} is its value at threshold, η is the coupling term, $\Delta t_m = \Delta\omega_m t - \phi_0(t)$, where $\Delta\omega_m = \omega_m - \omega_0$ (the angular frequency detuning between the free-running SL laser and the ML_m, $m = 1, 2$), $\phi_0(t)$ is the SL phase, α is the linewidth enhancement factor and N_0 is the carrier density at transparency. J is proportional to the injected current density and τ_s is the lifetime for spontaneous emission and non-radiative recombination. It is also important to define the injection strength $K_{1,2}$ as the ratio of the injected field ($E_{1,2}$) to the free-running SL field (E_{os}), which is given by $E_{os} = \sqrt{\tau_p(J - N_{th}/\tau_s)}$ where τ_p is the photon lifetime. Results are expressed in terms of the stability map of K_1 versus Δf_1 (where $\Delta f = \Delta\omega/2\pi$).

In order to calculate the carrier density, we numerically integrate the rate equations (1)–(3) using the Runge–Kutta method. The normalized carrier density is then taken as the ratio between ΔN and N [7]. The theoretical power spectra were obtained by applying a fast Fourier transform (FFT) to a chosen time window of the SL electric field time series. The parameters used, most of which are obtained through experimental characterization of the SL [6], are shown in Table 1.

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Table 1
Parameters used in our simulation

Parameter	Symbol	Value	Unit
Wavelength	λ	1556.6	nm
Linewidth enhancement Factor	α	3	
Differential gain	G_N	1.4×10^{-12}	$m^3\,s^{-1}$
Carrier lifetime	τ_s	0.43	ns
Photon lifetime	τ_p	1.8	ps
Coupling rate	η	9×10^{10}	s^{-1}
Transparency carrier density	N_0	1.1×10^{24}	m^{-3}
Threshold carrier density	N_{th}	1.5×10^{24}	m^{-3}
Normalized injection current	I/I_{th}	2	

3. Results and discussion

It is well known that the injection of an optical signal into the cavity of another laser can generate many nonlinear dynamics. One of which, is the locking phenomenon [6], where the SL is locked to the frequency of the ML in a region called locking bandwidth (LB). This region is generally illustrated as a function of the injection level (K) and the frequency detuning (Δf) in the so-called stability map. Fig. 1 shows the original LB (solid lines) under the injection of one ML. Apart from the gray area, which will be discussed shortly, the SL is well locked to the ML within the LB and exhibit self-pulsation phenomenon elsewhere in the map [6]. Inside the LB, the SL is stably locked in a small region in the negative detuning side (not shown here, see [6] for details). To study the effect of an additional (second) signal, we constantly inject the ML_2 at a fixed point (the solid square at −35 dB, −0.5 GHz) and rescan the stability map to examine the dynamical behavior of the SL. The resulting map is shown in Fig. 1.

It was found that the injection of the second signal creates a region that depends on the position of the ML_2, where the SL is locked to the second signal and hence this region is called the secondary locking region (SLR) [9] (note that the shape of the SLR here is different from that in [9] as a result of the difference in the position of ML_2). In other words, the SL is always locked to ML_2 at −0.5 GHz in the gray region (Fig. 1) and to the ML_1 in the white area within the LB. That is because ML_2 in the SLR overcomes the ML_1 where the latter locks the signal in the remaining area of the LB. The last region (white region outside the LB, top right corner) indicates the area where the SL is not locked to either signal and the system exhibits beat phenomena. It is worth mentioning that the stable locking defined in [9] cannot be maintained here, i.e. under relatively strong dual optical injection, and the locking investigated here is always unstable locking (the SL peak follows the ML peak with the presence of observable side peaks, greater than −20 dB relative to the injection locked SL peak [9]). This is a general feature of multiple injection especially at high injection and low frequency detuning, which is the case investigated in this article. The SLR was correlated with the frequency-pulling phenomenon associated with the carrier density variation [6,9]. More about this region with the experimental verification can be found in [7,9].

To explore the nonlinear dynamics of electron density under dual optical injection, we first investigate this dynamics as a function of frequency detuning at constant injection levels (indicated by the vertical lines in Fig. 1) and as a function of injection level at constant frequency detuning (indicated by horizontal lines in Fig. 1).

Fig. 2 shows the normalized electron density versus frequency detuning at −35 dB (corresponding to the left vertical line in Fig. 1). The normalized carrier density is proportional to the population inversion as mentioned before. This quantity has its steady-state value in the stable locking region. However, this region does not exist in our case and rather the carrier density is averaged over the temporal variations and the mean value is plotted in the figure. The solid lines represent the dynamics of electrons under single optical injection (without ML_2) whereas the dashed lines are the dynamics under dual optical injection. The boundaries of the LB and the SLR are also indicated. Under single optical injection, the dynamics of the carrier density exhibits anti-symmetrical behavior within and outside the LB with enhanced carriers in the positive detuning side and depleted in the negative detuning side. This phenomenon is well investigated in [6]. Since the injection level of ML_2 is equal to that of ML_1 (−35 dB), the dynamics under dual optical injection seems to copy the same asymmetrical behavior, which

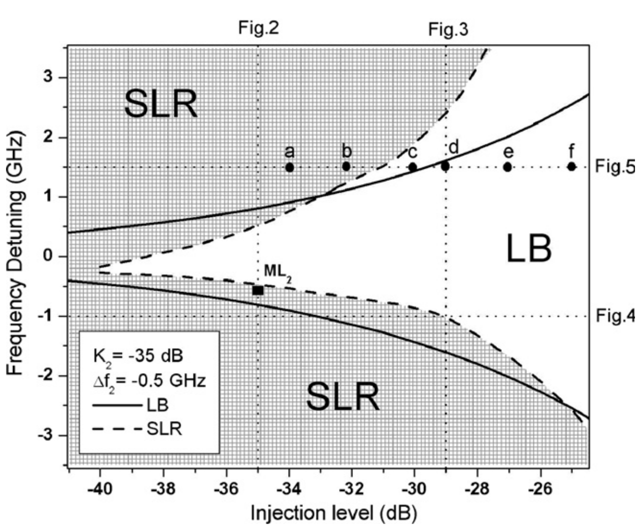

Fig. 1. The theoretical stability map of the SL under the injection of two ML. The solid lines represent the original LB (the SL is locked to ML_1, this is in the absence of ML_2) and the dashed lines (gray area) represent the SLR (the SL is locked to ML_2, in the presence of ML_1), note that the SL is locked to ML_1 in the white area within the LB and does not show any locking outside both regions (the SLR and the LB). The solid square indicates the position where the ML_2 is injected (−35 dB, −0.5 GHz). The vertical dotted lines correspond to Figs. 2 and 3 whereas the horizontal lines correspond to Figs. 4 and 5 as indicated. The marked points (a–f) represent the operation points where the power spectra in Fig. 6 are taken. These points are also shown in Fig. 5.

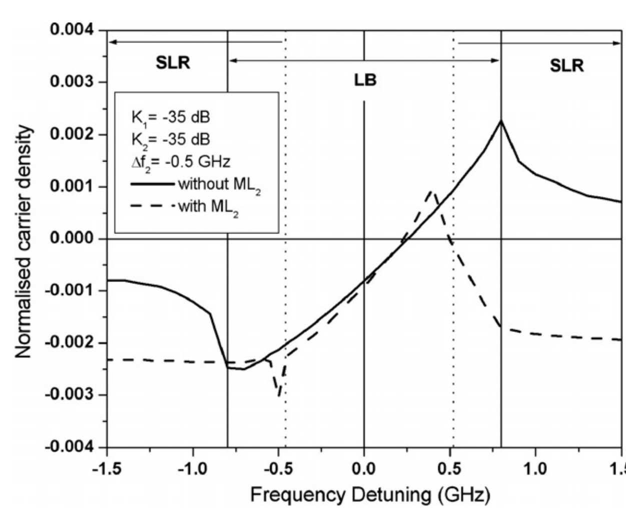

Fig. 2. Electron density variation as a function of frequency detuning at an injection level of $K_1 = -35$ dB (the left vertical line in Fig. 1). The dynamics under single and dual optical injection are indicated by the solid and dashed lines, respectively. The boundaries of the LB and the SLR are shown for clarity. ML_2 is constantly injected at −0.5 GHz and −35 dB.