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Side-Mode-Suppression-Ratio of Injection-Locked Fabry–Perot Lasers

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The paper deals with numerical simulation and theoretical study of injection-locked Fabry–Perot semiconductor laser diodes and their transient and steady-state properties. Motivation for this research comes from the fact that Fabry–Perot semiconductor laser diodes seem to be good candidates for transmitters applied in optical network units of new generation wavelength-division-multiplexed passive optical networks. We base our model on the full scale multimode rate equation system, which comprises all supported longitudinal modes of Fabry–Perot semiconductor laser diode, providing its high reliability and broad applicability. We analyze the influence of bias current and spontaneous emission coupling factor on injection-locking characteristics of Fabry–Perot semiconductor laser diodes and find that injection power of the master laser required to maintain an acceptable side-mode-suppression-ratio strongly depends on these parameters. The emphasis of our investigation is on spontaneous emission coupling factor, since its value is often assumed rather than thoroughly calculated or measured. As we show in the paper, variations of this parameter may affect theoretical results and their comparison with experimental data.

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1. Introduction

Recent progress in high-speed optical transmission systems has enabled fast development of access passive optical networks (PONs). The next-generation PONs require the use of cost-effective technologies in order to increase the scalability of these networks to more end users, longer spans, and higher bit rates. A key solution for this realization of the extended reach high-capacity PONs is the combination of wavelength-division-multiplexing (WDM) with advanced electronic processing schemes and simple optical solutions. One of the crucial subsystems in these networks is the optical network unit (ONU), which is responsible for upstream transmission to optical line terminal (OLT) or central office (CO). One possible solution for an ONU based on WDM technologies uses injection-locked transmitters [1]. In the injection locking technique, the light of the master laser (tunable laser in the CO) is injected into the Fabry–Perot (FP) slave laser in the ONU [1]. In this way, the slave laser is locked to the wavelength of the master laser, and every ONU needs only one FP laser instead of much more expensive tunable laser. The injection locking system is very simple, and it consists of two lasers and of an optical isolator between them, which is necessary in order to disable backward reflections from the slave laser.

In this paper, we theoretically investigate the direct modulation properties of injection-locked Fabry–Perot semiconductor laser diodes (FP-LDs). We investigate influences of various parameters on transient and steady-state properties of injection-locked FP-LDs. In Sect. 2 we give our theoretical model considering multimode injection-locked laser rate equations and gain profile as well as numerical implementation of the model. In Sect. 3 we present our results and discuss them. We find that spontaneous emission coupling factor and bias current have great impact on injection-locked laser properties.

2. Theoretical model

2.1. Rate equations and gain profile

The model of injection-locked semiconductor laser is based on multimode rate equations [2–4] with extra terms describing the locking phenomenon. These equations describe carrier density n, photon density for every mode S_m and the phase difference ϕ_m between the phase in the injected and in the free-running state. It is the system of $2m+1$ nonlinear differential equations, where m stands for total number of modes

$$\frac{\mathrm{d}n}{\mathrm{d}t}=\frac{\eta_i I}{qV}-\frac{n}{\tau_\mathrm{c}}-\sum_m v_\mathrm{g} g_\mathrm{m} S_m, \tag{1}$$

$$\frac{\mathrm{d}S_m}{\mathrm{d}t}=\Gamma v_\mathrm{g} g_\mathrm{m} S_m-\frac{S_m}{\tau_\mathrm{p}}+\Gamma\theta\frac{n}{\tau_\mathrm{c}} +2k_\mathrm{c}\sqrt{S_\mathrm{inj}S_m}\cos\varphi_m, \tag{2}$$

$$\frac{\mathrm{d}\varphi_m}{\mathrm{d}t}=\frac{1}{2}\alpha v_\mathrm{g} g_\mathrm{m}-\Delta\omega+k_\mathrm{c}\sqrt{\frac{S_\mathrm{inj}}{S_m}}\sin\varphi_m. \tag{3}$$

Here η_i stands for internal quantum efficiency with value of 0.8, τ_c and τ_p are carrier and photon life-

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time, calculated to be 2 ns and 2.24 ps, respectively. $V = 4 \times 10^{-12}$ cm^3 is the volume of the active area, $v_g = c/n_r$ is group velocity with $n_r = 3.4$, $\Gamma = 0.5$ is the confinement factor, k_c is the external light coupling factor [3], which in our simulation has the calculated value of 1.6×10^{11} s^{-1}. S_{inj} is the injected photon density, $\alpha = 3$ is the linewidth enhancement factor and $\Delta\omega$ is the frequency detuning between the master laser and the slave laser. Parameter θ is the spontaneous emission coupling factor, defined as the ratio of spontaneous emission coupling rate to the lasing mode and total spontaneous emission rate.

Modal optical gain g_m is modeled as in [2]:

$$g(n,S,m) = \frac{1}{1+\left(\frac{\Delta m}{M}\right)^2}\frac{g_0}{1+\varepsilon S_m}\ln\left(\frac{n+n_s}{n_s+n_{tr}}\right), \quad (4)$$

where g_0, n_s and n_{tr} are gain modeling parameters, with values 2400 cm^{-1}, 1.3×10^{18} cm^{-3} and 2.2×10^{18} cm^{-3}, respectively [2]. We included nonlinear gain suppression which is modeled through parameter ε with value 1.5×10^{-17} cm^3 [2]. In Eq. (4) Δm is the mode number counted from the central mode ($\Delta m = 0$), which is assumed to be aligned with the gain peak, while M is the mode number where the gain decays to one half of its peak value.

2.2. Numerical implementation

In order to get full use of the rate equation model applied in this analysis, we base our calculation on the gain spectra dependence on the carrier concentration. The first step in our numerical procedure is to calculate the modal gain, the number of supported modes and parameter M. These parameters can be extracted from the gain spectrum profile. The profile of the gain spectrum for a fixed carrier concentration is approximated by a parabolic function. The function has two zeros corresponding to band gap energy and the difference of the quasi Fermi levels in the conduction (E_{fc}) and the valence (E_{fv}) band, while its vertex value is given by relation (4) (Fig. 1). In the implementation of this procedure, we assume bulk lattice-matched $In_{0.53}Ga_{0.47}As$ [2]. The difference of the quasi Fermi levels $E_{fc} - E_{fv}$ depends on the carrier concentration in the conduction and the valence band. The carrier concentration can be evaluated by integrating the density of the filled states in the conduction and the valence band over energy. Assuming the bulk material, the general form for the carrier concentration is given in the form of Fermi–Dirac integral [2]. In case of active region based on quantum wells, a similar procedure applies. However, the extracted parameters do not differ significantly when compared to the case of bulk active region. From semiconductor equilibrium condition $n = p$ we calculate $E_{fc} - E_{fv}$ for a given carrier density, using global approximation of Fermi–Dirac integral [2]. Our calculation shows that for injection currents of the slave laser from I_{th} to $8I_{th}$ and for the standard cavity length of FP-LD of $L = 250$ μm, the variation of the number of supported modes is negligible. In this case the number of modes is around $m = 93$, while the modal spacing is 1.2 nm. In addition to this, for a given current range, M is estimated to be 23, while Δm goes from 0 to 46. This means that our rate equation system (1)–(3) has $2m+1$ equations and it is solved by adaptive Runge–Kutta algorithm of fourth order, with step size of 1 ps.

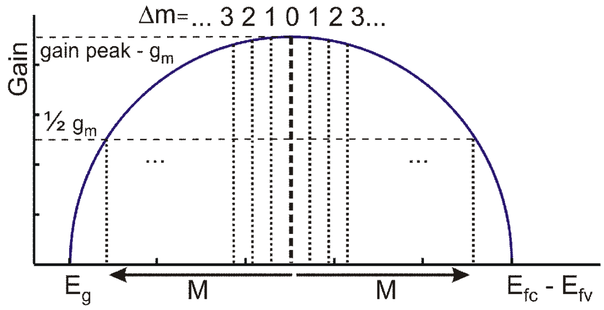

Fig. 1. The gain profile approximation, mode number Δm and half-width mode number M.

3. Results and discussion

Injection locking technique brings many reported advantages like less relaxation oscillations, shorter turn-on-delay time, larger modulation bandwidth, less chirp etc. [3–8]. Figure 2 shows transient regime of a free-running as well as an injection-locked semiconductor laser. In the free-running regime the central mode is the most pronounced one, and all other modes have less power in comparison. We applied injection in the fifth mode with injection power $P_{inj} = -0.76$ dBm, and with no frequency detuning. The slave laser is biased with $1.2I_{th}$. We adopt $\theta = 1 \times 10^{-5}$ as the most common value in semiconductor lasers. As it can be seen in Fig. 2, injection reduces amplitudes of the relaxation oscillations, and in addition to this, amplifies the injected mode while suppressing the others. The quality of mode suppression is quantified through the side-mode-suppression-ratio (SMSR), which is defined as a ratio between a given mode and the strongest side-mode [1].

In the case of WDM-PONs, SMSR is the figure of merit for successfully achieved monomode output for broad wavelength range of slave FP-LDs, after they are locked or seeded by the master, i.e. tunable laser in OLT. In other words, the injection locked regime can be considered monomode when SMSR is above a certain level, usually 30 dB [1, 3]. In this paper, we investigate how the number of injection-locked modes changes with the injection power of the master laser in OLT. In order to do that, it is necessary to take into consideration the full scale model of the rate equations which comprises as many as possible free-running modes. To the best of our knowledge, the problem of injection locking in WDM-PONs has been treated by models based on few modes [1, 3], which could cause significant discrepancy with experimental results. In addition to this, the influence of spontaneous

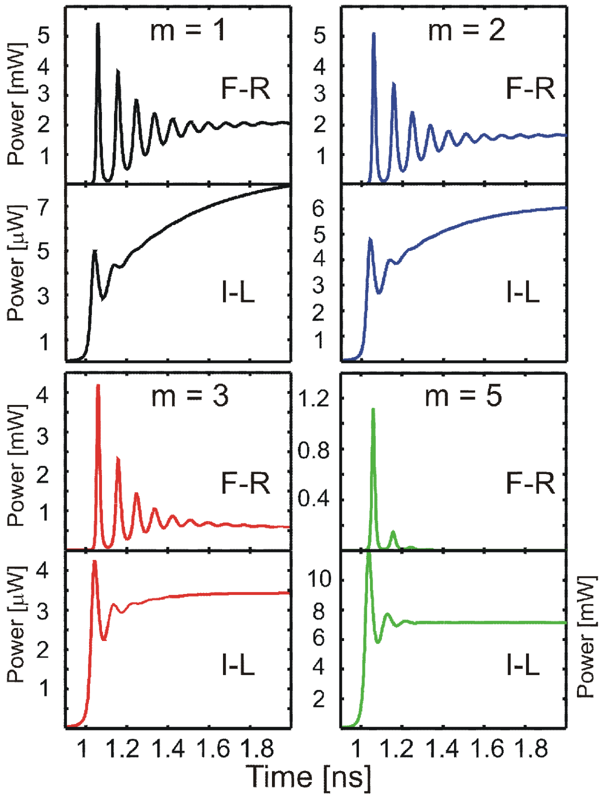

Fig. 2. Transient regime of free-running (F-R) and injection-locked (I-L) FP-LD with injection in the 5th mode.

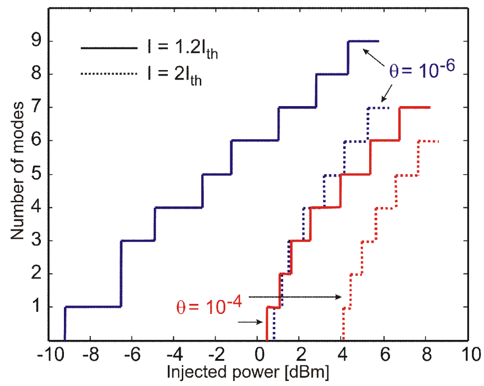

Fig. 3. The number of modes achieving SMSR $=$ 30 dB versus injected power for different values of I and θ.

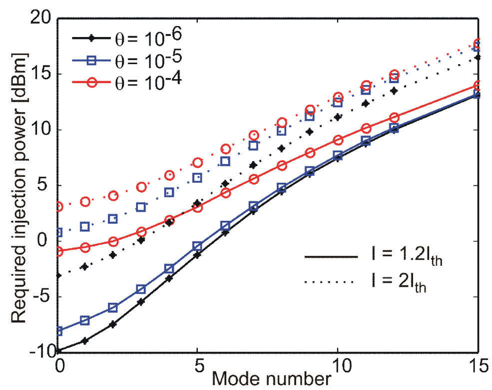

Fig. 4. Required injection power for SMSR $=$ 30 dB for different values of I and θ.

emission coupling factor has not been previously considered in the treatment of injection-locked FP-LDs. As we show here this factor can significantly affect the level of injection power required to achieve SMSR $\geq$ 30 dB. The exact value of this parameter needs to be calculated from the exact spontaneous emission distribution throughout the modes. In general, this is a mode dependent parameter, but we assumed that it is constant for all modes. Depending on the semiconductor laser type and material and geometrical parameters, this factor can vary in the wide range, from 1×10^{-6} to 1×10^{-4}.

Figure 3 shows the number of modes for which SMSR reaches 30 dB versus injected power of the master laser, with bias current and θ as parameters. In Fig. 3, the number of modes is in the form $1+n$, where 1 stands for the central mode, and n is the number of side modes on one side of the central mode. Since our model predicts symmetrical distribution around the central mode, the total number of modes that can achieve SMSR $\geq$ 30 dB is $1+2n$. For smaller bias currents ($1.2I_{\text{th}}$), the injected power necessary to achieve monomode regime is smaller than for larger currents ($2I_{\text{th}}$). Although the currents do not differ too much, the difference of the injected power is significant and can reach almost 10 dBm. A similar behavior can be observed when θ is increased from 1×10^{-6} to 1×10^{-4}. However, the influence of θ becomes more pronounced for smaller bias currents than for larger. In addition to this, the difference of injected power for a fixed number of modes is smaller when the number of modes is larger. The reason for the increase of the injection power with an increase of the bias current is related to the ratio of number of photons in the free-running regime and the number of injected photons. As a matter of fact, the injected photons can prevail and sustain stimulated emission at a certain mode much easier if the number of already existing free-running photons is smaller. This situation occurs when the bias current is smaller. Similarly, an increase of θ leads to the increase of the number of spontaneously emitted photons supporting a particular mode and thus requiring an increase of injected photons in order to switch between two modes.

Figure 4 depicts minimal required injection power for a certain mode to achieve SMSR $=$ 30 dB for three representative values of θ and two bias currents. The figure shows only the right side of the mode spectrum, while the left side of the spectrum is mirror-symmetrical. The effect of the bias current and θ on the minimal injection power is similar as for the results shown in Fig. 3. It is interesting to notice that the required minimal injection power increases more rapidly for larger θ and smaller bias currents. The results shown in Fig. 4 are in agreement with experimental data in [3], but clearly point out the importance of spontaneous emission coupling factor.

4. Conclusion

In this work we simulate transient and steady-state regimes of injection locked FP-LDs by using full scale model of the rate equations comprising 93 modes. This investigation is relevant for implementation of FP-LDs in ONUs used in WDM-PONs. We analyze the influence of bias currents and spontaneous emission coupling factor on SMSR, number of modes for which SMSR fulfills the monomode condition and the injection power levels necessary to achieve monomode output. The results of our simulation show that larger bias currents and larger spontaneous emission coupling factor require larger injection powers to achieve the monomode regime. From this we conclude that more attention should be paid to the spontaneous emission coupling factor when investigating injection-locking phenomenon, since the variation of this factor can affect theoretical results and their comparison with experimental data.

Acknowledgments

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