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Salah Abdulrhmann, Moustafa Ahmed, Takaharu Okamoto and Minoru Yamada
Department of Electrical and Electronic Engineering, Kanazawa University, Kanazawa, 920-8667, Japan
Phone: 81-76-234-4866, Fax: 81-76-234-4870
Email: 5502abdu@ec.t.kanazawa-u.ac.jp

Abstract: Possibilities of pulsing and chaotic operations of semiconductor lasers under strong optical feedback were theoretically predicted by a new and unified model and experimentally confirmed.

Introduction: Semiconductor lasers have a wide range of applications such as fiber-optic communication systems. In applications as power sources in the fiber amplifiers, the lasers are used with an external cavity which consists of an optical fiber and an optical fiber grating (OFG) in order to increase the optical power and to select the lasing wavelength. Since these pumping lasers are designed to have small reflectivity at the front facet and rather larger reflectivity at the OFG, the lasers suffer very strong optical feedback into the laser cavity [1]. However, these lasers happen to show changes of both the output power and lasing spectrum. The theoretical models of semiconductor lasers under optical feedback so far have been limited to the cases that the feedback is rather weak or moderate [2]. In this paper, we proposed a new model of analysis to include cases of operation under very strong optical feedback. We found that the laser exhibits CW, chaos and pulsing operation depending on the operating conditions. The pulsing operation was theoretically predicted to characterize the strong optical feedback regime, and was observed experimentally as well in this paper.

Simulation model and results: Our model of analysis is shown in Fig. 1. We performed simulation of laser operation under optical feedback by integrating the following modified rate equations of the photon number S, the carrier number N and the optical phase θ:

$$\frac{dS}{dt} = \left\{ \frac{a\xi}{V}(N - N_g) - BS - G_{th0} + \frac{c}{n_r L}\ln|T| \right\} S + \frac{a\xi}{V} N \qquad (1)$$

$$\frac{d\theta}{dt} = \frac{\alpha a\xi}{2V}(N - \bar{N}) - \frac{c}{2n_r L}(\phi - \bar{\phi}) \qquad (2)$$

$$\frac{dN}{dt} = -\frac{a\xi}{V}(N - N_g)S - \frac{N}{\tau_s} + \frac{I}{e} \qquad (3)$$

where T is a function to take into account the optical feedback, and is given as

$$T = 1 - (1 - R_f)\sqrt{\frac{R_{ex}}{R_f}}e^{-j\psi}\sqrt{\frac{S(t-\tau)}{S(t)}}\frac{e^{j\theta(t-\tau)}}{e^{j\theta(t)}} = |T|e^{-j\phi} \qquad (4)$$

which was treated in almost all previous models as [2]

$$\ln|T| \approx -(1 - R_f)\sqrt{\frac{R_{ex}}{R_f}}e^{-j\psi}\sqrt{\frac{S(t-\tau)}{S(t)}}\frac{e^{j\theta(t-\tau)}}{e^{j\theta(t)}}$$

where ψ is the phase difference between delayed light in the external cavity and the reflected field at the front facet of the laser cavity. The numerical integration was performed by applying the fourth order Runge-Kutta algorithm using a time interval of 5 ps. Periodic variations of the output power were shown in some operating conditions. Figure 2 shows the simulated output waveform and the corresponding power spectrum at $R_{ex}/R_f = 3.5$ and $I = 1.5I_{th}$. As shown in the power spectrum in Fig. 2(b), the first peak occurs at the external frequency $f_{ex} = 1/\tau$ and the rest of the peaks correspond to multiples of $1/\tau$. This may mean that the laser is locked at the external cavity frequency $1/\tau$. These effects were observed in our experiment as shown in Fig. 3, where R_{ex}/R_f =3.5 and $I=1.5I_{th}$. Lasing operations are classified theoretically into three types, namely: CW, chaos and pulsing operations. These operations are determined with many parameters, such as I/I_{th}, R_{ex}/R_f, ℓ and ψ. Figure 4 is a chart indicating the regions of these operations. The pulsing operation is induced in the case of $R_{ex}/R_f \geq 0.05$.

References: [1] T. Mukai and K. Ohtsuka, Phys. Rev. Lett. 55, 1711 (1985).
[2] R. Lang and K. Kobayashi, IEEE J. Quantum Electron. 16, 347 (1980).

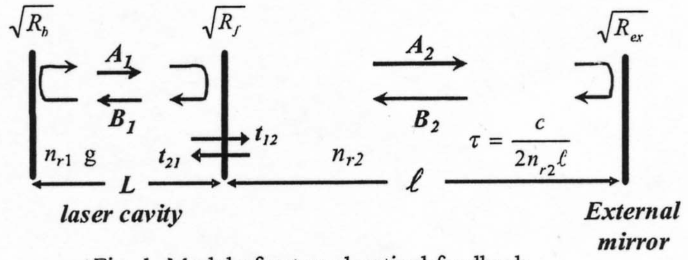

Fig. 1. Model of external optical feedback.

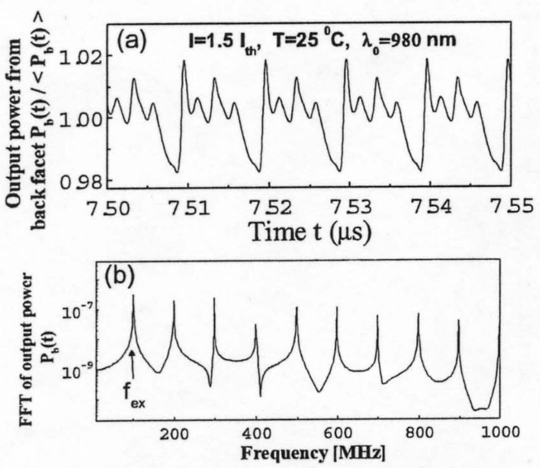

Fig. 2. Simulated (a) output waveform and (b) corresponding power spectrum

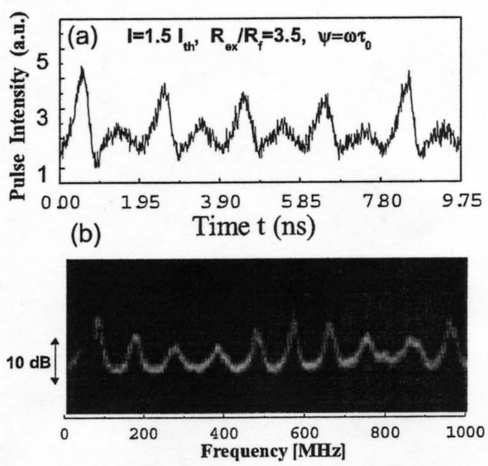

Fig. 3. Observed (a) output waveform, and (b) corresponding frequency spectrum

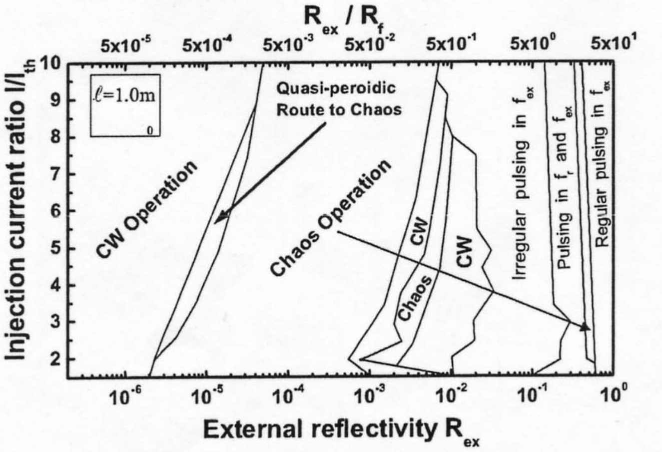

Fig. 4. Classification of laser operation under weak to very strong external optical feedback.