Dynamics of a semiconductor laser subject to a frequency-shifted optical feedback

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The dynamics of a semiconductor laser subject to a delayed and frequency-shifted optical feedback is numerically investigated. An appropriate shift of the optical frequency of the light fed back into the laser after a roundtrip in an external cavity is shown to lead to the generation of stable trains of pulses repeated at the external cavity frequency. This regime is robust and characterized by a rather small amplitude and time jitters. The impact of spontaneous emission noise on this regime is also investigated.

Introduction

Laser diodes are very sensitivity to external perturbations such as external, delayed, optical feedback. These perturbations, which are undesirable in most applications, lead to dynamical instabilities that in turn can degrade severely their spectral and temporal performances. When the feedback delay, i.e. the time that the light emitted by the laser takes to be re-injected into the laser after reflection on an external mirror, is much shorter than the relaxation oscillation period, the laser dynamics is characterized by the emission of package of pulses [1],[2]. Within each package, the pulses are interspersed by a time very close to the feedback delay but their amplitude is modulated by a slow envelope. In addition, the emission of each pulse goes with a progressive increase of the phase difference between the field inside the laser and the field fed back into the laser after a roundtrip in the external cavity, thus a gradual redshift of the laser output.

This system can be modified by a small blue shift of the light fed back into the laser in order to obtain the emission of stable trains of pulses [3]. I summarize these results in the following and I verify the robustness of this control method with respect to spontaneous emission noise.

Equations

The behavior of a single-mode laser diode subject to an external optical feedback is typically predicted by the Lang-Kobayashi equations [4]. Taking a frequency shift of the optical feedback and spontaneous emission into account, these equations read

$$\frac{dE}{dt} = \frac{1+i\alpha}{2}\left[G_N(N-N_0) - \frac{1}{\tau_p}\right]E + \kappa E(t-\tau)\exp(-i\omega_0\tau + i\Delta t) + F_E(t) \qquad (1)$$

$$\frac{dN}{dt} = \frac{I}{e} - \frac{N}{\tau_s} - G_N(N-N_0)|E|^2. \qquad (2)$$

$E(t)$ is the slowly varying complex electric field with $|E|^2 \equiv P$, P being the photon number inside the active region of the laser. $N(t)$ is the electron-hole pair number in the active layer. α is the linewidth enhancement factor. κ is the feedback rate, τ the feedback delay and $\omega_0\tau$ the feedback phase. Δ is the shift of the feedback light from the angular frequency of the isolated laser: $\Delta = 2\pi\delta$. τ_p and τ_s are respectively the photon and the carrier lifetimes. G_N is the differential gain and N_0 the value of N at transparency. The term $F_E(t)$ is a Langevin noise force accounting for spontaneous emission noise with $<F_E(t)F_{E^*}(t')> = R_{sp}\delta(t-t')$ where R_{sp} is the spontaneous emission rate. I is the electric current injected in the laser. Most numerical values of the laser's parameters are those that have been used in Ref. [1],[2], namely $\alpha = 5$, $\tau_p = 1.11$ ps, $\tau_s = 1710 \times \tau_p$, $\eta = 0.1 \times \tau_p$, $\tau = 250 \times \tau_p$, $\Omega\tau = 0$. $I = 1.009 \times I_{th}$.

Figure 1(a) sketches a laser diode subject to a conventional optical feedback and Fig. 1(b) a laser diode subject to a frequency-shifted optical feedback. The optical feedback frequency is Doppler shifted by an acousto-optic modulator (AOM).

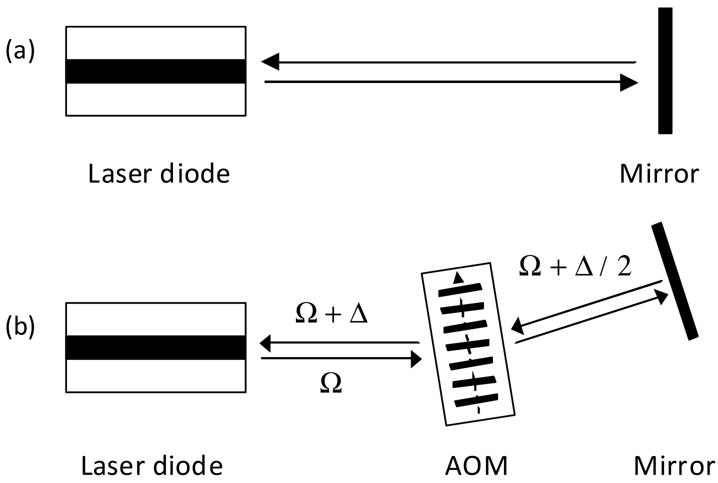


Fig. 1. Schematics of a laser diode subject to a conventional optical feedback (a) and to a frequency-shifted optical feedback (b).

Numerical results

With the numerical values considered here, the laser diode subject to a conventional optical feedback emits packages of pulses [see Fig. 1(a)]. The pulses are repeated with a frequency close to the external cavity frequency but their amplitude is modulated on a much longer time scale. The progressive variation of the pulses' amplitude is a consequence of the fact that the external cavity frequency (3.6 GHz) is much larger that the relaxation oscillation frequency (490 MHz for the solitary laser). Indeed, the carrier population does not have the time to relax between two pulses.

With an adequate frequency shift of the field fed back into the laser, the system continues to emit pulses at the external cavity frequency but with almost constant amplitude as shown in Fig. 2(b). In other words, the useful feature of the system, the regular emission of pulses, is conserved while the detrimental feature, the slow modulation of the pulse amplitude, is corrected.

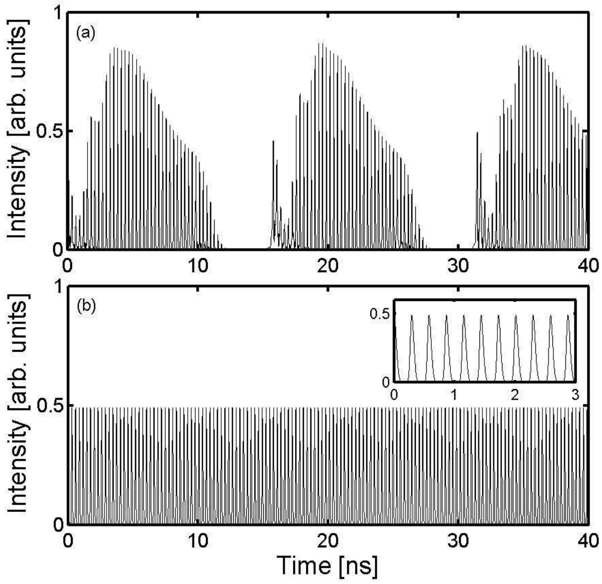


Fig. 2. Time trace of the output of the laser subject to optical feedback without frequency shift (a) and with an adequate frequency shift $\delta = 400$ MHz (b).

The bifurcation diagram displayed in Fig. 3 summarizes the laser dynamics with respect to a frequency shift up to 5 GHz. The diagram reveals that a control of the laser dynamics is achieved from 120 MHz to 4.2 GHz. Within this range, which widely exceeds the typical range (from a few tens to several hundreds of megahertz) of commercially available AOMs, the period of the pulses remains very close to the feedback delay (278 ns) [Fig. 4(a)].

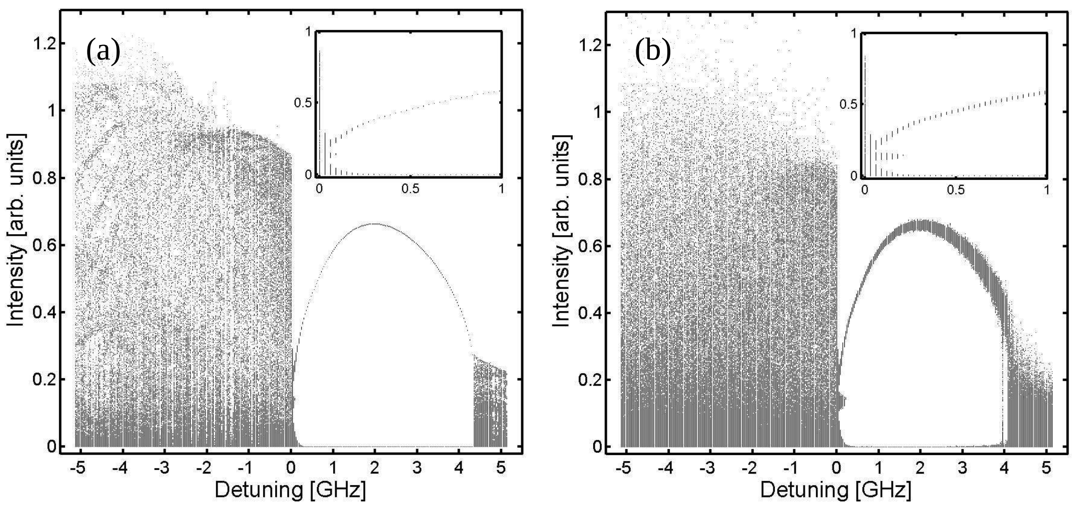
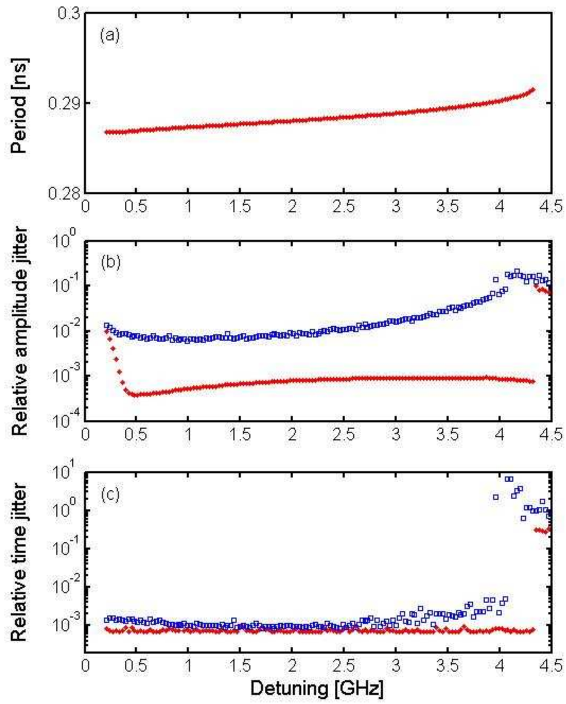


Fig. 3. Extrema of the laser intensity with respect to frequency shift. Spontaneous emission noise is neglected in (a) and taken into account in (b). Insets are enlarged views in the range $\delta = 0$ to 1 GHz.



The effect of spontaneous emission noise has been investigated. Simulations predict that its impact is limited for realistic values of the spontaneous emission rate. In the present case, I consider $R_{sp} = 10^{11}$ s^{-1}. The bifurcation diagram is blurred but the region where control is achieved remains unchanged [Fig. 3(b)]. The amplitude jitter increases by an order of magnitude while the time jitter remains close to 0.1% of the pulse period [Fig. 3(c)].

Fig. 4. (a) Period, (b) relative amplitude jitter and (c) relative time jitter of the pulses as functions of the optical feedback frequency shift. In (b) and (c) dots and squares correspond to $R_{sp} = 0$ and 10^{11} s^{-1}, respectively.

Conclusion

Subject to optical feedback, a laser diode can operate in the so-called regular pulse package regime when the feedback delay is much shorter than the period of its the relaxation oscillations. However, an adequate frequency shift of the field fed back into the laser can lead to the generation of pulses with small period and time jitters. According to numerical predictions, this control can be achieved with commercially available acousto-optic modulator and it is robust to a realistic level of spontaneous emission noise.

References

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