Generation of regular optical pulses in VCSELs below the static threshold

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Abstract

We demonstrate theoretically that vertical-cavity surface emitting lasers (VCSELs) under asymmetrical current modulation and external optical injection can generate subnanosecond regular optical pulses below the static threshold. Asymmetrical triangular pump modulation allows the laser to generate irregular pulses, on average, below the static threshold. Injection plays a stabilizing role, reduces the standard deviation of the generated pulses and increases their averaged amplitude. This phenomenon can reduce heating of the laser active medium and can be useful in Information Technology.

Keywords: vertical-cavity surface-emitting lasers (VCSELs); optical injection; polarization; semiconductor lasers

1. Introduction

Directly-modulated vertical cavity surface emitting lasers (VCSELs) are very attractive light sources for both digital and analog photonic communication systems. They have low threshold current, high modulation bandwidth, and emit a single-longitudinal mode and circular output beams that result in high coupling efficiencies into optical fibers. Under current modulation, nonlinear effects such as period doubling, chaos and multistability can arise [1, 2]. In present paper, we theoretically investigate VCSEL dynamics under triangular current modulation and external optical injection. In previous study [3], it was shown that the VCSEL under asymmetric triangular current modulation generates irregular optical pulses in two orthogonal linear polarizations. In this case, VCSELs can operate, on average, below the static threshold. This phenomenon can reduce heating of the VCSEL active medium. Heating is one of the most important VSCELs performance limiting factor. Unfortunately asymmetrically modulated VCSELs generate optical pulses with both irregular amplitude and polarization. Here, we propose to stabilize the VCSEL output by small external optical injection.

2. Model

Polarization properties of VCSEL are described by the spin-flip model extended to optical injection [4]:

$$\dot{E}_x = k(1+i\alpha)\left[(N-1)E_x + inE_y\right] - i\left(\gamma_p + \Delta\omega\right)E_x - \gamma_a E_x + kE_{inj}\cos(\psi) + \sqrt{\beta_{sp}}\xi_x,$$

$$\dot{E}_y = k(1+i\alpha)\left[(N-1)E_y - inE_x\right] + i\left(\gamma_p - \Delta\omega\right)E_y + \gamma_a E_y + kE_{inj}\sin(\psi) + \sqrt{\beta_{sp}}\xi_y,$$

$$\dot{N} = \gamma_N\left[\mu(t) - N\left(1+|E_x|^2+|E_y|^2\right) - in\left(E_yE_x^* - E_xE_y^*\right)\right],$$

$$\dot{n} = -\gamma_s n - \gamma_N\left[n\left(|E_x|^2+|E_y|^2\right) + iN\left(E_yE_x^* - E_xE_y^*\right)\right], \tag{1}$$

where k is the field decay rate, γ_N is the decay rate of the total carrier population, γ_s is the spin-flip rate which accounts for the mixing of carrier populations with different spins, α is the linewidth enhancement factor, γ_a and γ_p are linear anisotropies representing dichroism and birefringence, $\Delta\omega$ is the detuning parameter, Ψ is the angle between horizontal and the direction of the optical injection linear polarization, β_{sp} is the noise strength, $\xi_{x,y}$ are uncorrelated Gaussian white noises, and $\mu(t)$ is the normalized injection current parameter: the static threshold is-at $\mu_{th,s}=1$.

The current is modulated with an asymmetric triangular signal of amplitude $\Delta\mu$, rising from μ_0 a time interval T_1 and falling back to μ_0 a time interval T_2. One modulation cycle is: $\mu(t)=\mu_0+\Delta\mu(t/T_1)$ for $0\le t\le T_1$, $\mu(t)=\mu_0+\Delta\mu\left[1-(t-T_1)/T_2\right]$ for $T_1\le t\le T_1+T_2$. The average current, $\mu_{ave}=\mu_0+\Delta\mu/2$, is independent of the modulation period, $T=T_1+T_2$. The asymmetry of the modulation is characterized by the parameter $\alpha_a=T_1/T$ with $0\le\alpha_a\le1$.

3. Results and Discussion

The equations were simulated with typical VCSEL parameters [5]: $k=300\ ns^{-1}$, $\alpha=3$, $\gamma_N=1\ ns^{-1}$, $\gamma_a=0.5\ ns^{-1}$, $\gamma_p=50\ rad/s$, $\gamma_s=50\ ns^{-1}$, and $\beta_{sp}=10^{-6}\ ns^{-1}$. Current modulation leads to the emission of optical pulses even when, on average, the injection current is below the threshold [3]. There is an optimal modulation asymmetry, typically $\alpha_a\cong0.8$, for which the averaged intensity and the averaged pulse amplitude reach their maximum value, and for this asymmetry the dispersion of the pulse amplitude reaches its minimum value. Figure 1(a)–(f) displays time traces of the $I_x = |E_x|^2$ and $I_y = |E_y|^2$ for three injection values and the same parameters: average current value $\mu_{ave} = 0.87$, asymmetry $\alpha_a = 0.8$, detuning $\Delta\omega = 0$, $\Psi = \pi/4$ (injection in both polarizations).

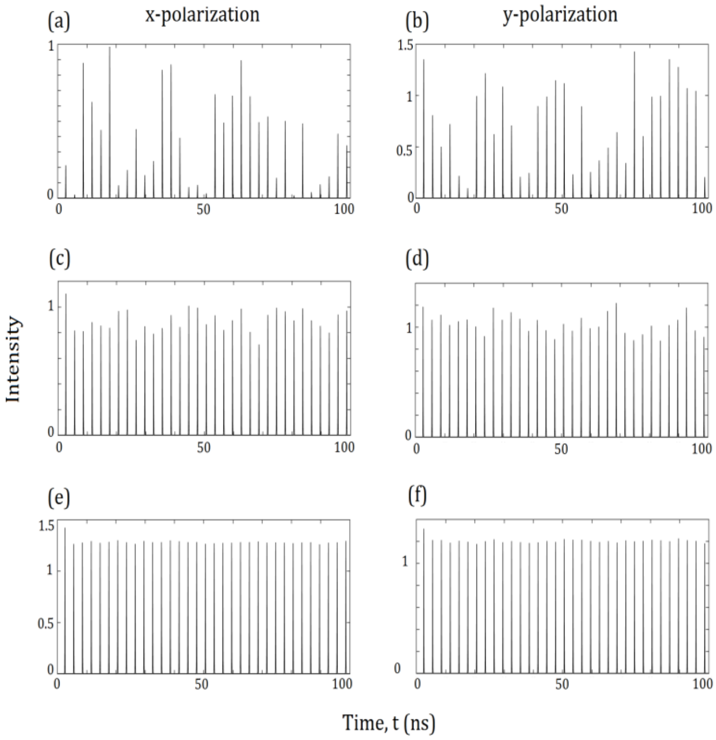

Fig. 1. Time traces of intensities of the orthogonal linear polarization: (a), (b) $E_{inj} = 0$, (c), (d) $E_{inj} = 10^{-5}$, (e), (f) $E_{inj} = 10^{-4}$.

Figure 2(a) displays standard deviation of the intensity of the pulses. It can be observed that injection of the optical signal leads to more regular pulses. Also, injection leads to increasing of the mean value of generated pulses for both polarizations (Figure 2(b)).

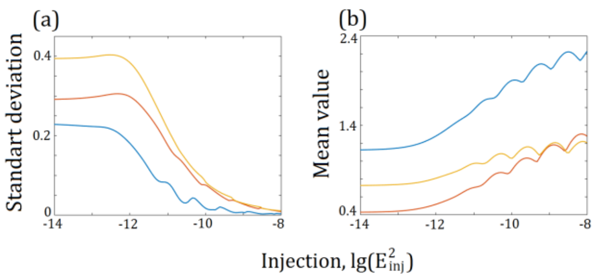

Fig. 2. Standard deviation of the intensity of the pulses (a). Mean of the intensity of the pulses (b). Red is the x-polarization, yellow is the y-polarization and blue is the total intensity.

Figure 3(a) displays the standard deviation of the total intensity of the pulses. Figure 3(b) displays the mean of the total intensity of the pulses. The mean of the total intensity has the maximum value for the angle $\Psi = \pi/2$ (parallel optical injection). Standard deviation has minimum for $\Psi = \pi/2$ and angle $\Psi = 0$. x-polarization vanishes for parallel optical injection and y-polarization vanishes for orthogonal optical injection ($\Psi = 0$).

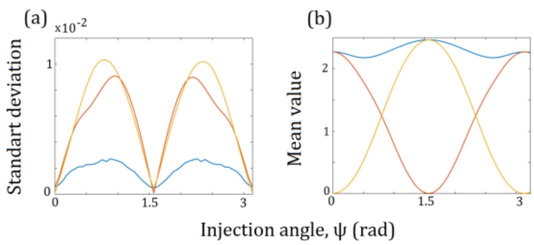

Fig. 3. Standard deviation of the intensity of the pulses (a). Mean of the intensity of the pulses (b). $E_{inj} = 10^{-4}$. Red is the x-polarization, yellow is the y-polarization and blue is the total intensity.

The frequency detuning between injected and generated radiation $\Delta\omega$ is the important parameter of the model. Figures 4(a), (b) display the standard deviation of the total intensity of the pulses and the mean of the total intensity of the pulses for the $\Psi = \pi/4$. The standard deviation of the total intensity of the pulses has minimum for the $\Delta\omega \approx \gamma_p = 50$. The mean of the total intensity of the pulses has maximum for the same detuning value. For the $\Psi = 0$, the standard deviation of the total intensity of the pulses has minimum for $\Delta\omega = 0$ and the mean of the total intensity of the pulses has maximum for the same detuning value. For the $\Psi = \pi/2$, the standard deviation of the total intensity of the pulses has minimum for $\Delta\omega \approx \gamma_p = 50$ and the mean of the total intensity of the pulses has maximum for the same detuning value.

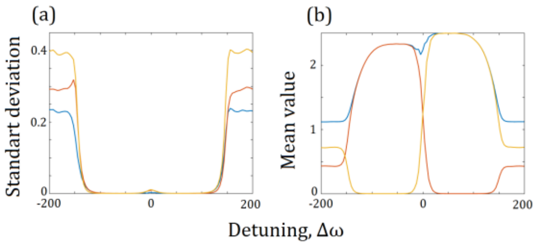

Fig. 4. Standard deviation of the intensity of the pulses (a). Mean of the intensity of the pulses (b). $E_{inj} = 10^{-4}$, $\Psi = \pi/4$. Red is the x-polarization, yellow is the y-polarization and blue is the total intensity.

It was shown that small external optical injection stabilizes both amplitude and polarization of asymmetrically modulated VCSEL. Generation of quasiregular optical pulses is possible for the injection value $E_{inj} = 10^{-4}$, which is about $5 \cdot 10^{-9}$ of the output radiation average intensity. Method proposed in this paper provides a generation of regular optical pulses in VCSELs below the static threshold. Control of the output radiation polarization is also possible.

4. Conclusion

Summarizing, we have theoretically investigated dynamics of the asymmetrically modulated VCSEL using the spin-flip model extended to optical injection. We showed that external optical injection stabilizes the VCSEL output. Injection of the optical signal decreases the standard deviation and increases the mean value of generated pulses. Also, the standard deviation has minimum for parallel optical injection (injection only in y-mode). For the wide range of parameters, optical injection has the most stabilizing effect for $\Delta\omega \approx \gamma_p$, which means that injection is coherent to y-mode. However, there is the possibility of smooth adjustment of the polarization of the generated pulses by varying the injection angle Ψ.

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