

Influences of orthogonal optical feedback on the polarization switching of multi-transverse-mode in vertical-cavity surface-emitting lasers subject to orthogonal optical injection

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In this paper, influences of orthogonal optical feedback on the polarization switching (PS) of multi-transverse-mode in vertical-cavity surface-emitting lasers (VCSELs) subject to orthogonal optical injection have been investigated. The results show that the injection power required for PS in VCSELs subject to orthogonal optical injection can be decreased through introducing orthogonal optical feedback.

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1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) have many attractive features compared to edge-emitting semiconductor lasers, such as low threshold current, low cost, circular output-beam profile and 2D arrays fabrication [1-2]. Although VCSELs are intrinsically single-longitudinal-mode devices, emission in multiple transverse and different polarization modes are usually found [3]. The linearly polarized (LP) modes emitted by solitary VCSEL are not well fixed and may generate polarization switching (PS) under the small changes of the injection current or the device temperature. Furthermore, high-order transverse mode may be excited for the large injection current.

Polarization switching performances of multi-transverse-mode VCSELs subject to orthogonal optical injections have also been investigated both theoretically and experimentally [4]. In this paper, after introducing orthogonal optical feedback, the polarization switching performances of multi-transverse-mode in VCSELs subject to orthogonal optical injections have been analyzed, and the influences of orthogonal optical feedback have also been presented.

2. Theory

We treat the case of VCSELs that can operate in the fundamental (LP₀₁) and in the first-order (LP₁₁) transverse mode. In the basis of the linearly polarized modes and considering radial symmetry of the cavity, the optical field

can be written as [5-6]:

$$\vec{E}(r, t) = \{[E_{0x}(t)\psi_{0x}(r) + E_{1x}(t)\psi_{1x}(r)]\vec{x} + [E_{0y}(t)\psi_{0y}(r) + E_{1y}(t)\psi_{1y}(r)]\vec{y}\}e^{ik\alpha t} + c.c \quad (1)$$

where ψ_{0j} and ψ_{1j} are the modal profiles of the j -polarized LP₀₁ and LP₁₁ modes, respectively, obtained by solving the Helmholtz equation [6-7], E_{0j} and E_{1j} are the modal amplitudes of these modes, in which the subscript j stands for the x - or y -polarized mode, respectively, k is the electric field decay rate and α is the linewidth enhancement factor [8].

Based on spin flip model (SFM) [9-10] and spatial hole burning (SHB) effects [11], the equations for a VCSEL (named slave VCSEL), which is orthogonally injected from another VCSEL (master VCSEL), with a orthogonal optical feedback, can be described by [4, 12]:

$$\begin{aligned} \dot{E}_{0x} = & k(1 + i\alpha) (E_{0x}(g_{0x} - 1) + iE_{0y}g_{0xy}) - (\gamma_a + i\gamma_{p0})E_{0x} + \frac{k_{0x}}{\tau_{in}}e^{i\Delta\omega t} \\ & + \eta_{0x}E_{0y}(t - \tau)e^{-i\omega_{0y}\tau} + \sqrt{\frac{\beta}{2}}(\sqrt{N + n_{\xi_{0+}}}(t) + \sqrt{N - n_{\xi_{0-}}}(t)) \end{aligned} \quad (2a)$$

$$\begin{aligned} \dot{E}_{0y} = & k(1 + i\alpha) (E_{0y}(g_{0y} - 1) + iE_{0x}g_{0yx}) - (\gamma_a + i\gamma_{p0})E_{0y} \\ & + \frac{k_{0y}}{\tau_{in}}e^{i\Delta\omega t} + \eta_{0y}E_{0x}(t - \tau)e^{-i\omega_{0x}\tau} - i\sqrt{\frac{\beta}{2}}(\sqrt{N + n_{\xi_{0+}}}(t) - \sqrt{N - n_{\xi_{0-}}}(t)) \end{aligned} \quad (2b)$$

$$\begin{aligned} \dot{E}_{1x} = & k(1+i\alpha) (E_{1x}(g_{1x} - \kappa_r) + iE_{1y}g_{1xy}) + i\gamma_p^{tr} E_{1x} \\ & - (\gamma_a + i\gamma_{p1})E_{1x} \\ & + \frac{k_{1x}}{\tau_{in}} e^{i\Delta\omega t} + \eta_{1x} E_{1y}(t-\tau) e^{-i\omega_{1y}\tau} \\ & + \sqrt{\frac{\beta}{2}} \left(\sqrt{N + n_{\xi_{1+}}}(t) + \sqrt{N - n_{\xi_{1-}}}(t) \right) \end{aligned} \quad (2c)$$

$$\begin{aligned} \dot{E}_{1y} = & k(1+i\alpha) (E_{1y}(g_{1y} - \kappa_r) + iE_{1x}g_{1yx}) + i\gamma_p^{tr} E_{1y} \\ & - (\gamma_a + i\gamma_{p1})E_{1y} \\ & + \frac{k_{1y}}{\tau_{in}} e^{i\Delta\omega t} + \eta_{1y} E_{1x}(t-\tau) e^{-i\omega_{1x}\tau} \\ & - i\sqrt{\frac{\beta}{2}} \left(\sqrt{N + n_{\xi_{1+}}}(t) - \sqrt{N - n_{\xi_{1-}}}(t) \right) \end{aligned} \quad (2d)$$

$$\begin{aligned} \frac{\partial N(r,t)}{\partial t} = & I(r) + D\nabla_{\perp}^2 N - \gamma_e \\ & \times \left[N \left(1 + \sum_{i=0,1} \sum_{j=x,y} |E_{ij}|^2 \psi_{ij}^2(r) \right) - in \sum_{i=0,1} (E_{ix}E_{iy}^* - E_{iy}E_{ix}^*) \times \psi_{ix}(r)\psi_{iy}(r) \right] \end{aligned} \quad (2e)$$

$$\begin{aligned} \frac{\partial n(r,t)}{\partial t} = & -\gamma_s n + D\nabla_{\perp}^2 N - \gamma_e \\ & \times \left[n \sum_{i=0,1} \sum_{j=x,y} |E_{ij}|^2 \psi_{ij}^2(r) - in \sum_{i=0,1} (E_{ix}E_{iy}^* - E_{iy}E_{ix}^*) \times \psi_{ix}(r)\psi_{iy}(r) \right] \end{aligned} \quad (2f)$$

where τ is the external-cavity round-trip time, $\tau_{in} (= 2L/v_g)$, where v_g is the group velocity, L is the length of the cavity) is the round-trip time of VCSEL. γ_s is the spin-flip rate, γ_e is the carrier decay rate, γ_a is the dichroism parameter, and κ_r is the relative loss of the LP₁₁ mode with respect to the LP₀₁ mode. β is the spontaneous emission coefficient, and D is the diffusion coefficient. $N(r,t)$ is the total carrier number and $n(r,t)$ is the difference between population inversions of opposite spins. $I(r)$ represents a uniform current injection of over a circular disk with radius a , and then $I(r) = I$ if $r < a$ and $I(r) = 0$, elsewhere. The detuning $\Delta\omega = \omega_{inj} - \omega_{th}$, where ω_{inj} is the frequency of the master VCSEL and $\omega_{th} = (\omega_{0x} + \omega_{0y})/2$, is the central frequency detuning between the two polarizations of the fundamental mode. ω_{ij} ($i=0, 1$; $j=x, y$) are the frequency polarizations of fundamental and first-order mode. η_{ij} is the feedback rates of the j -polarized i -transverse mode, here we choose $\eta_{0x} = \eta_{0y} = \eta_0$ and $\eta_{1x} = \eta_{1y} = \eta_1$. The γ_{p0} (γ_{p1}) accounts for frequency splitting between the orthogonal polarizations of the LP₀₁ (LP₁₁), and the γ_p^{tr} accounts for frequency splitting between two transverse modes with the same polarization

[4, 13]. The gain g_{ij} ($i=0, 1$; $j=x, y$) normalized to the threshold gain is defined as:

$$g_{ij} = \frac{\int_0^\infty N(r,t) \psi_{ij}^2(r) r dr}{\int_0^\infty \psi_{ij}^2(r) r dr} \quad (3)$$

and $g_{i,jk}$ ($i=0, 1$; $jk=xy, yx$) is given by

$$g_{i,jk} = \frac{\int_0^\infty n(r,t) \psi_{ij}(r) \psi_{ik}(r) r dr}{\int_0^\infty \psi_{ij}^2(r) r dr} \quad (4)$$

It should be pointed out that the modal gains for the x and y polarizations are different due to the different optical mode profiles. The injection strength k_{ij} ($i=0, 1$; $j=x, y$) is given by [8]:

$$k_{ij} = \left(\frac{1}{\sqrt{R}} - \sqrt{R} \right) \sqrt{\eta_{inj}} \sqrt{P_{inj,ij}}, \quad (5)$$

where R is the output-mirror reflectivity, η_{inj} is the coupling efficiency of the injection light to the optical field in the laser cavity, and $P_{inj,ij}$ is the injection power in the j -polarization of the i -transverse mode. Spontaneous emission noise processes are modeled by the terms $\xi_{\pm}$ taken as complex Gaussian white noise sources of zero mean and delta-correlated in time, and the carrier distribution is integrated over the active region:

$$\bar{N} = \frac{\int_0^a N(r,t) r dr}{a^2}, \quad \bar{n} = \frac{\int_0^a n(r,t) r dr}{a^2}. \quad (6)$$

Additionally, the rate equations of master VCSEL are similar to Eq. (2) except that there are not injection and feedback terms.

3. Results and discussion

The rate equations mentioned above can be numerically solved by the fourth-order Runge-Kutta method. During the calculations, time and space integration steps of 1ps and 0.1um have been used, respectively, and the other used parameters are [4, 12]: $L = 1\mu m$, $a = 3\mu m$, $k = 300ns^{-1}$, $\alpha = 3$, $\gamma_e = 0.55ns^{-1}$, $\gamma_s = 91ns^{-1}$, $\gamma_a = -0.81ns^{-1}$, $D = 1cm^2s^{-1}$, $\beta = 10^{-1}s^{-1}$, $\eta_{inj} = 1$, $R = 0.995$, $\kappa_r = 1.2$, $\tau = 1.666ns$, $\gamma_{p0} = \gamma_{p1} = 7.5 \times 10^9 rad/s$, $\gamma_p^{tr} = 1.605 \times 10^{12} rad/s$, $v_g = 8.6 \times 10^9 cms^{-1}$, $\omega_{0x} = 2.155320 \times 10^{15} rad/s$, $\omega_{0y} = 2.155335 \times 10^{15} rad/s$, $\omega_{1x} = 2.156925 \times 10^{15} rad/s$, $\omega_{1y} = 2.156940 \times 10^{15} rad/s$.

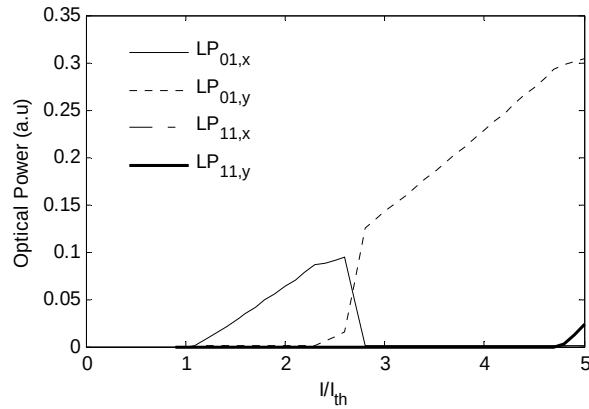


Fig. 1. Light-current characteristics of master multi-transverse-mode VCSEL.

Fig. 1 is the light-current characteristics of master VCSEL. With the increase of the biased current, the VCSEL begins to emit in the fundamental mode $LP_{01,x}$, and PS ($LP_{01,x}$ mode switch to $LP_{01,y}$ mode) will occur when the biased current is increased to about $2.7I_{th}$ (I_{th} is the threshold current). The higher order mode LP_{11} will appear when the current is higher than $4.8I_{th}$.

In the following, we will fix the biased current at $2I_{th}$ both in slave VCSEL and master VCSEL, and investigate the influence of the orthogonal optical feedback on the PS performances of multi-transverse-mode in VCSELs subject to orthogonal optical injection.

Fig. 2 shows the injection power required for PS in slave VCSEL subject to orthogonal optical injection without optical feedback. The injection power emitted from master VCSEL can be adjusted by a variable attenuator, and the varying injection power has been normalized to the output power of master VCSEL and has been taken in logarithmic scale. For a given value of the frequency detuning, we change the injection power step by step and calculate the average of each polarized transverse mode over the last nanosecond (of 20-ns duration) of each step. The PS occurs when the total y-polarized power (contained average power of $LP_{01,y}$ and $LP_{11,y}$ mode) becomes larger than the total x-polarized power. From this diagram, we can see that there are two minimums in the injection power required for switching, which appears around 0 and 220 GHz. At the first minimum, the polarization switches between the fundamental transverse modes: the $LP_{01,x}$ mode switches to the $LP_{01,y}$ mode when the injection power increase to a determined value, which has been shown in Fig. 3 (a). At the second minimum, the polarization switches mainly between the $LP_{01,x}$ and $LP_{11,y}$ modes, which can be seen in Fig. 3 (b).

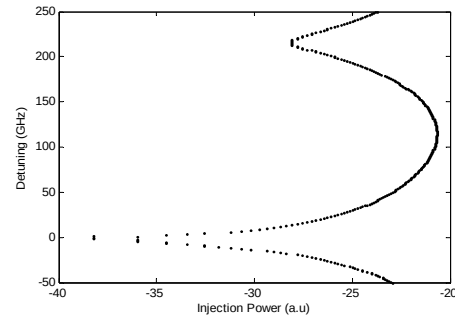


Fig. 2. Injection power required for PS in slave VCSEL subject to orthogonal optical injection without optical feedback.

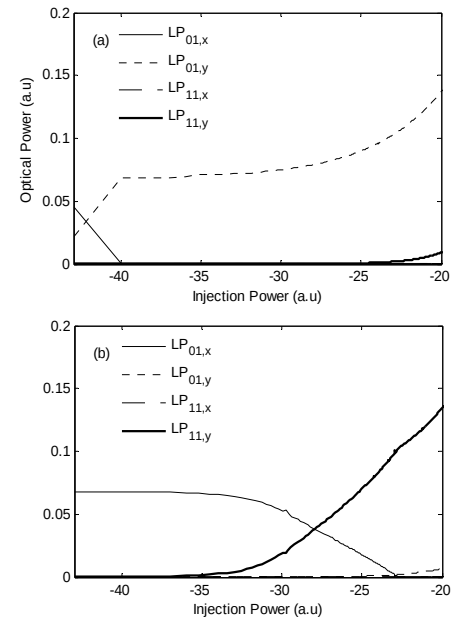


Fig. 3. Variation of the output powers for each polarized transverse modes with the orthogonal injection power for frequency detuning (a) 0 GHz, and (b) 220 GHz.

Influences of orthogonal optical feedback on PS performances of slave VCSEL subject to orthogonal optical injection are shown in Fig. 4, where the dash line (solid line) corresponds to with (without) orthogonal optical feedback. From this diagram, it can be seen that the orthogonal optical feedback is helpful for decreasing of the injection power required for PS. With the increase of the orthogonal optical feedback rate, the injection power required for PS will be decreased more severely. Moreover, the influences of the orthogonal optical feedback on the injection power required for PS is more obvious for larger frequency detuning.

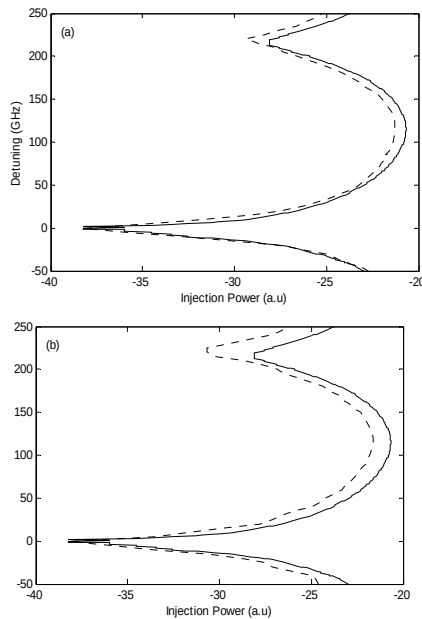


Fig. 4. Injection power required for PS in slave VCSEL subject to orthogonal optical injection with orthogonal optical feedback, where (a) and (b) are for the feedback rates are 5 ns^{-1} and 12 ns^{-1} , respectively. Dash line is for the case with optical feedback and the solid line is for the case without optical feedback.

4. Conclusions

The influences of orthogonal optical feedback on polarization switching performances of multi-transverse-mode in VCSELs subject to orthogonal optical injection have been investigated numerically in this paper. The results show that orthogonal optical feedback is helpful for decreasing the injection power required for PS, especially for the larger frequency detuning between master VCSEL and slave VCSEL. With the increase of the orthogonal optical feedback rate, the injection power required for PS is decreased more severely.

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