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Numerically Simulate the Polarization Behavior of the 1550 Nm Vertical-cavity Surface-emitting Lasers with Negative Optoelectronic Feedback

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Abstract: Based on the Spin-flip Model (SFM), we numerically investigated the polarization switching dynamics of 1550 nm Vertical-cavity Surface-emitting Lasers (VCSELs) subjected to Negative Optoelectronic Feedback (NOEF). The results show that the multiple polarization switching points are shifted to lower injection currents with increasing the optoelectronic feedback strength. With further increase of the feedback strength, the 1550 nm VCSEL subjected to NOEF emits only in the y-polarization mode; the x-polarization mode is completely suppressed over the entire current range. Meanwhile, the 1550 nm VCSEL exhibits interesting nonlinear dynamics in the two linear polarized directions when the feedback delay time is varied.

Key words: Polarization switching, 1550 nm vertical-cavity surface-emitting lasers (VCSELs), negative optoelectronic feedback (NOEF)

INTRODUCTION

Compared with conventional Edge-emitting Semiconductor Lasers (EELs), Vertical-cavity Surface-emitting Lasers (VCSELs) possess many own unique advantages, such as low threshold current, low cost, single-longitudinal-mode operation, circular output-beam profile and easy large-scale integration into two-dimensional arrays (Hurtado *et al*., 2010). Previous researches have demonstrated that EELs exhibit a variety of nonlinear dynamics under external perturbations including optical injection (Simpson *et al*., 1997; Hwang and Liu, 2000), optical feedback (Mork *et al*., 1992) or optoelectronic feedback (Lin and Liu, 2003; Xia *et al*., 2007). The dynamics include polarization switching, chaos, bistability and injection locking. As for VCSELs, a wide variety of nonlinear dynamics of short-wavelength VCSELs under different external disturbances have been investigated theoretically (Gatare *et al*., 2009; Sciamanna and Panajotov, 2006; Zhang *et al*., 2007) and experimentally (Gatare *et al*., 2006; Hong *et al*., 2004). Recently, long-wavelength VCSELs emitting at λ>1000 nm have received more and more special attention. Accordingly, related theoretical and experimental results on the polarization dynamics of long-wavelength VCSELs (especially at the important telecom wavelength of 1550 nm) under external perturbations have been reported intensively (Homayounfar and Adams, 2007; Valle *et al*., 2008; Quirce *et al*., 2012; Xie *et al*., 2013). However, to the best of our knowledge, studies on polarization switching in 1550 nm VCSELs with Optoelectronic Feedback (OEF) are very scarce. In comparison to optical injection and optical feedback, OEF provides a flexible and reliable way for polarization control on VCSELs because of its convenience to be electrically controlled and insensitivity to optical phase variations (Giacomelli *et al*., 1989; Liao and Sun, 2013). Therefore, the polarization switching dynamics of 1550 nm VCSELs subjected to OEF should be paid attention and deserve investigation.

In this study, we numerically simulate the polarization switching behavior of the 1550 nm VCSELs with Negative Optoelectronic Feedback (NOEF). The key parameters of the model, that give rise to different polarization switching behaviors, are the optoelectronic feedback strength and the feedback delay time. We investigate the polarization dynamics for various values of the feedback strength. The impact of the feedback delay time on the polarization switching is also studied.

SYSTEM MODEL AND THEORY

Figure 1 illustrates the schematic diagram of a polarization switching system based on a 1550 nm VCSEL with NOEF. The laser output is divided into two parts by a Beam Splitter (BS). One part is converted to an electronic signal and fed back into the laser by a Photoelectronic Detector (PD) and an Electronic Amplifier (EA). The other is divided into two polarization optical

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beams by a Polarization Beam Splitter (PBS). These two polarization optical beams are simultaneously observed optically and electronically using an electronic detected system composed of a PD and a digital Oscilloscope (OSC).

Our numerical study is based on the spin-flip model (SFM) (San Miguel *et al*., 1995) which has been largely used in comparison with experiments. The rate equations for VCSEL with NOEF can be described by (Zhang *et al*., 2007):

$$\frac{dE_x}{dt} = \kappa(1+i\alpha)[(N-1)E_x + inE_y] - (\gamma_a + i\gamma_p)E_x \tag{1}$$

$$\frac{dE_y}{dt} = \kappa(1+i\alpha)[(N-1)E_y - inE_x] + (\gamma_a + i\gamma_p)E_y \tag{2}$$

$$\frac{dN}{dt} = -\gamma_e N(1+P) + \gamma_e \mu[1 - \eta\frac{P(t-\tau)}{P_0}] - i\gamma_e n(E_y E_x^* - E_x E_y^*) \tag{3}$$

$$\frac{dn}{dt} = -\gamma_s n - \gamma_e nP - i\gamma_e N(E_y E_x^* - E_x E_y^*) \tag{4}$$

where, subscripts x and y represent x and y linear polarized modes, respectively. E is the slowly varied complex amplitude of the field, N is the total carrier inversion between the conduction and valence bands, n accounts for the difference between carrier inversions for the spin-up and spin-down radiation channels, κ is the cavity delay rate, α is the linewidth enhancement factor, γ_e is the decay rate of total carrier population, γ_a is the gain anisotropy and γ_p is the birefringence rate, γ_s is the spin relaxation rate, τ is the feedback delay time, μ is the normalized injection current (μ takes the value 1 at threshold), η is the feedback index corresponding to the strength of feedback, $P = |E_x|^2+|E_y|^2$ is the normalized output power and P_0 is the free-running output power.

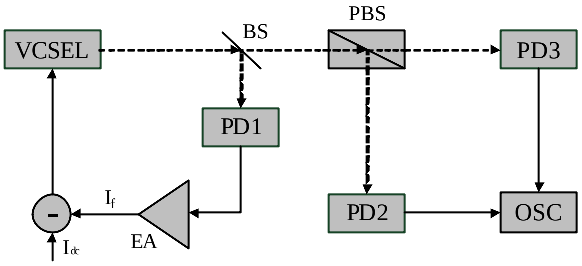

Fig. 1: Schematic diagram of a polarization switching system based on a 1550 nm VCSEL with NOEF. BS: Beam splitter; PD: Photoelectronic detector; EA: Electronic amplifier; PBS: Polarization beam splitter; OSC: Digital oscilloscope

RESULTS AND DISCUSSION

Equation 1-4 can be numerically solved by adopting the fourth-order Runge-Kutta algorithm and the values of the used parameters are shown in Table 1 (Al-Seyab *et al*., 2011).

Figure 2 displays the polarization-resolved P-I curve of the free-running 1550 nm VCSEL, where the normalized injection current μ is changed from 0 to 3. τ is fixed at 3 ns. For $1<\mu<2.18$, only the y-polarization mode oscillates. Once μ is larger than 2.18, the x-polarization mode starts to oscillate and the y-polarization mode will be suppressed.

Firstly, we investigate the effect of optoelectronic feedback strength on the polarization switching dynamics. Figure 3 shows the numerically simulated P-I curve of the 1550 nm VCSEL subject to NOEF for various values of the feedback strength. The feedback delay time is fixed at 3 ns. Figure 3a shows the P-I curve of the 1550 nm VCSEL when the feedback index η is 0.07. It shows that a single polarization switching point exists after the stand-alone polarization switching point. When the feedback index η is increased to 0.14, as shown in Fig. 3b, more polarization

Table 1: SFM parameters

Symbol	Description	Value and units
κ	Cavity delay rate	125 GHz
α	Linewidth enhancement factor	2.2
γ_e	Electron density decay rate	0.67 GHz
γ_a	Gain anisotropy	0.02 GHz
γ_p	Birefringence rate	192 GHz
γ_s	Spin relaxation rate	1000 Ghz

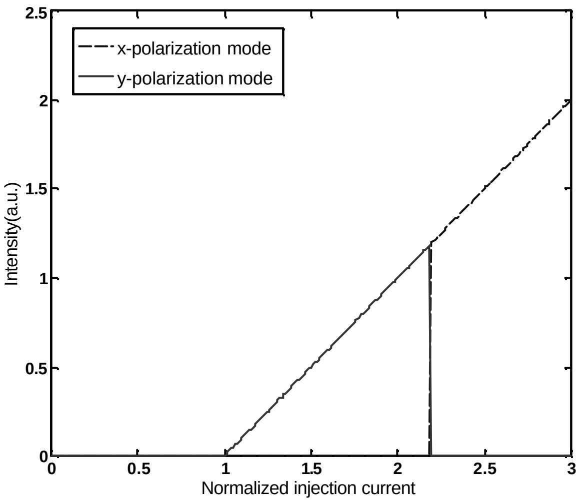

Fig. 2: Polarization-resolved P-I curve of a free-running 1550 nm VCSEL, where the dash line stands for x-polarization mode and solid line stands for y-polarization mode

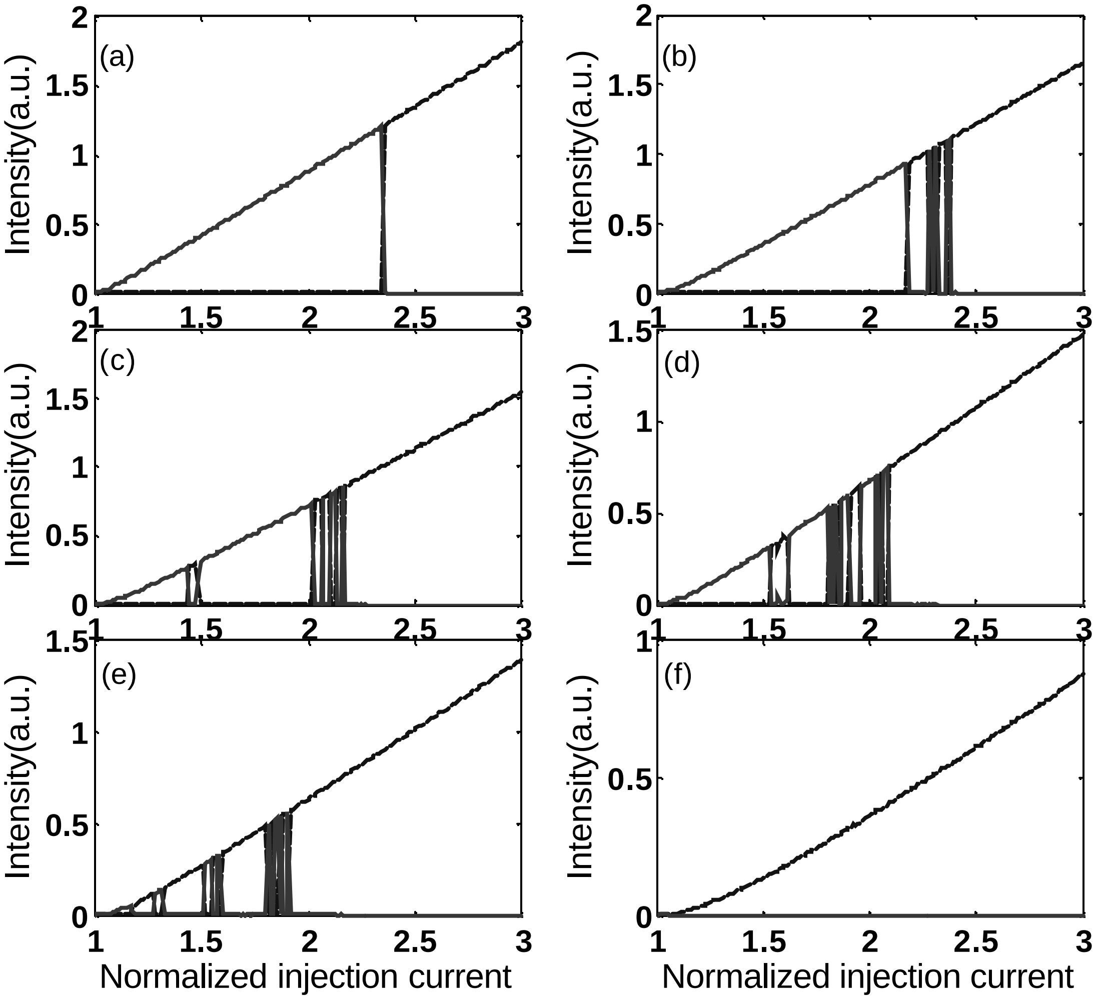

Fig. 3(a-f): Polarization-resolved P-I curve of the 1550 nm VCSEL subjected to NOEF for various values of the feedback strength. The dash line stands for x-polarization mode and solid line stands for y-polarization mode. The feedback indexes are (a) 0.07, (b) 0.14, (c) 0.20, (d) 0.24, (e) 0.29, (f) 0.90.

switching arises for injection currents that are higher than the stand-alone polarization switching current. The phenomenon of two-polarization-mode competition is observed. Further increasing the feedback index η to 0.20, as shown in Fig. 3c, one obvious phenomenon is the emergence of polarization switching in smaller injection current. Polarization mode competition phenomenon is also observed in the region of low injection currents. When the feedback index η is increased to 0.24 and 0.29, polarization switchings are shown in Fig. 3d and Fig. 3e. From previous diagrams, we can found that with increasing feedback strength the multiple polarization switchings move to lower injection currents. The region of polarization mode competition becomes small. Figure 3f shows the P-I curve with the value of feedback index η is 0.90. It is shown that the polarization switching disappears and the y-polarization mode is completely suppressed in the total range of injection currents for strong enough feedback.

Figure 4 displays the last polarization switching point current (μ_{PS}) for various values of the feedback strength. When the feedback strength η is increased from 0 to 0.14, there is only one polarization switching and the polarization switching point current increases from 2.18 to 2.375 slowly. Once the η is larger than 0.14, more polarization switching emerge. The last polarization switching point current shifts to lower injection current.

Next, the influence of optoelectronic feedback delay time on the polarization switching is studied. Figure 5 displays the simulation P-I curve of the 1550 nm VCSEL subject to NOEF for different values of the feedback delay time. The feedback index η is fixed at 0.20. Figure 5a

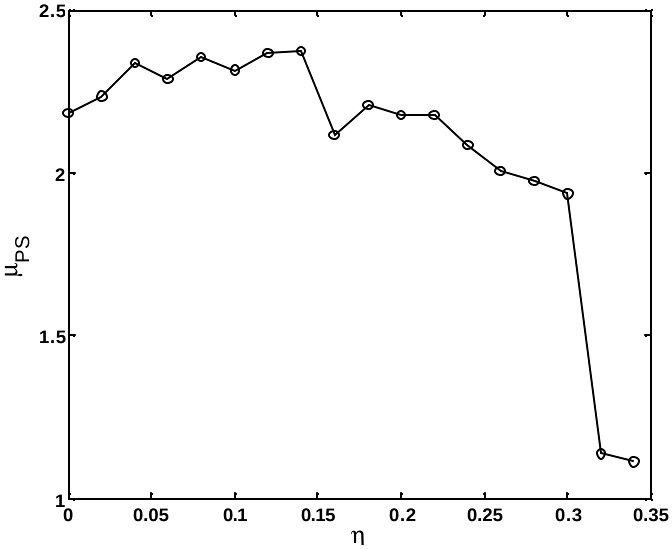

Fig. 4: Last polarization switching point current (μ_{PS}) for various values of the feedback strength

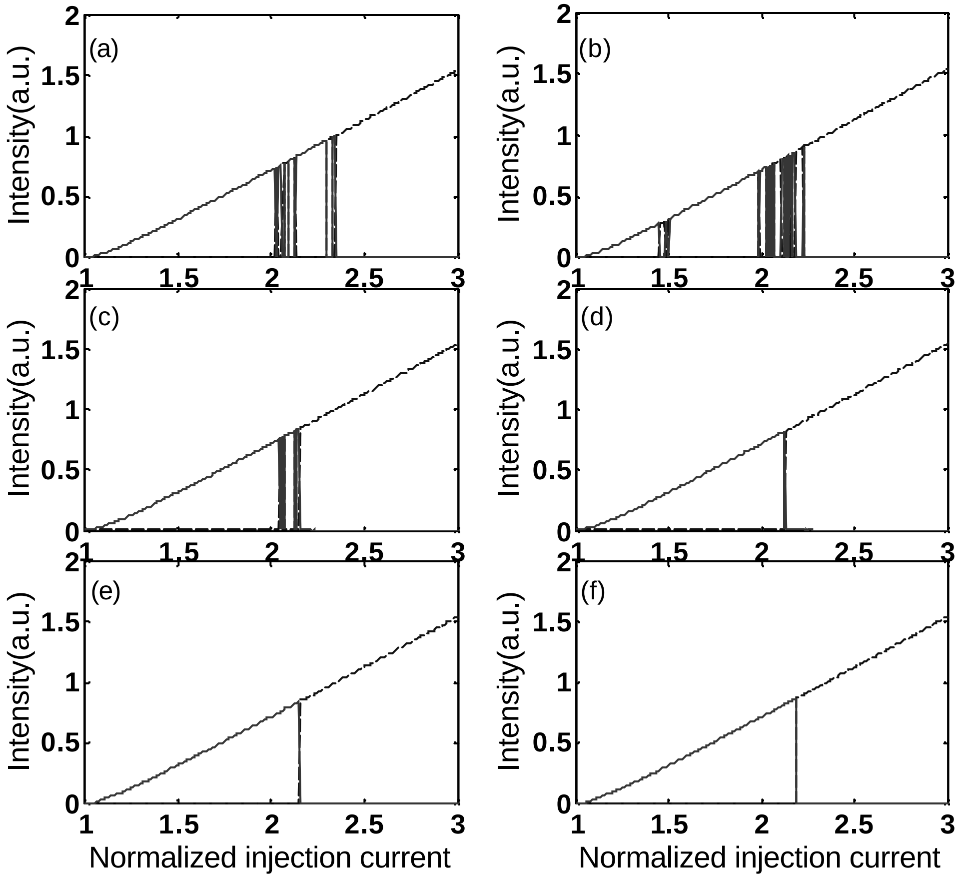

Fig. 5(a-f): Polarization-resolved P-I curve of the 1550 nm VCSEL subjected to NOEF for various values of the feedback delay time. The dash line stands for x-polarization mode and solid line stands for y-polarization mode. The numerical values of feedback delay time are (a) 1 ns, (b) 3 ns, (c) 5 ns, (d) 7 ns, (e) 9 ns, (f) 11 ns

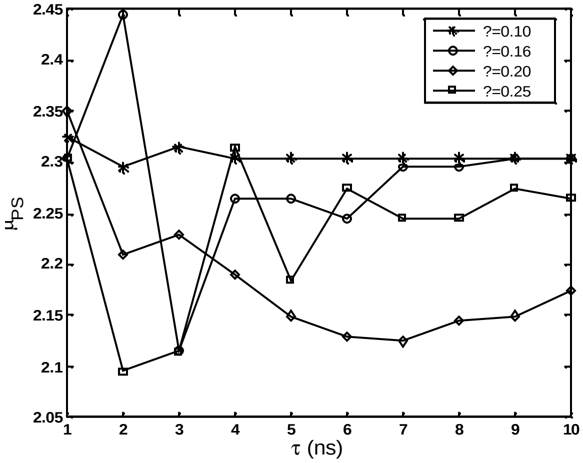

Fig. 6: Last polarization switching point current (μ_{PS}) for various values of the feedback delay time.

shows the P-I curve of the 1550 nm VCSEL with the feedback delay time τ is 1 ns. It shows that multiple polarization switchings exist at high injection current. Both polarization modes compete in the region of high injection currents. When the feedback delay time is increased to 3 ns, as shown in Fig. 5b, more polarization switchings arises for injection currents lower than the stand-alone polarization switching current. With a further increase in the feedback delay time to 5 ns and 7 ns, as shown in Fig. 5c and Fig. 5d, the polarization switching which exists at low injection current disappears and the polarization switching for injection currents near the stand-alone polarization switching current decreased. From this we can draw a conclusion that, with the increasing of feedback delay time, multiple polarization switchings are also transferred to lower injection currents. With continued increase of the feedback delay time to 9 ns and 11 ns, as shown in Fig. 5e and Fig. 5f, there is only one polarization switching for the injection current near the stand-alone polarization switching current. This shows that the multiple polarization switchings disappear and the stable polarization emission is observed within the entire injection current range.

Figure 6 shows the last polarization switching point current (μ_{PS}) for various values of the feedback delay time. For short delays, multiple polarization switchings are observed while for long delays, depending on the value of τ the polarization switching is suppressed and the polarization emission is observed. For different feedback strength, there is stable polarization emission in a certain range of delay time. This suggest that if one does not wish to completely suppress the polarization switching but only to control the polarization state of the light, this can be achieved using NOEF, by adjusting the parameters η and τ.

CONCLUSION

In this study, we numerically simulate the polarization switching dynamics of 1550 nm VCSELs with NOEF. Under weak feedback strength, only one polarization switching point was observed. When increasing the optoelectronic feedback strength, the phenomenon of polarization mode competition is observed. The region where both polarization modes compete moves to lower injection currents. With further increase the optoelectronic feedback strength, the y-polarization mode was completely suppressed over the entire current range. The influence of feedback delay time on the polarization switching of 1550 nm VCSELs is also studied numerically. For short delays, multiple polarization switchings is clearly observed. With the increase of the delay time, the polarization emission tends to be stable.

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