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Polarization bistability characteristics of optical feedback vertical-cavity surface-emitting lasers after taking into account multiple trip external optical feedbacks

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Single trip feedback approximation is usually adopted in modelling the optical feedback vertical-cavity surface-emitting lasers (VCSELs) in order to simplify the theoretical treatment. In this paper, after considering the common case of existence of the multiple trip optical feedbacks, the polarization bistability (PB) properties in VCSELs is investigated numerically. The results show that the polarization bistability performances, such as the width of the bistablity loop, the swith-on and swith-off current, obtained by multiple trip, are different from those obtained by single trip. With the increase of the strength of external optical feedback, the difference is further increased.

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Keywords: Vertical-cavity surface-emitting lasers (VCSELs), Polarization bistability, Multiple trip external optical feedback

1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) have received considerable attention in recent years [1-17] due to their potential applications in optical communications, optical interconnects and other fields. Comparing with edge-emitting semiconductor lasers, VCSELs have some notable advantages such as low threshold current, high modulation efficiency, dense packing capability and narrow circular beam profile etc. However, despite the cylindrical symmetry of the structure, the emission of VCSELs is commonly linearly polarized along one of two preferred orthogonal directions because of the cavity anisotropy. The two preferred orthogonal polarization directions are always defined as the X-polarization and Y-polarization. Specifically, when the bias current increases, the polarization may switches abruptly from X-polarization (or Y-polarization) to the orthogonal Y-polarization (or X-polarization) at some bias current I_a, and switches back to the orthogonal X-polarization (or Y-polarization) direction at another bias current I_b with decreasing bias current (usually $I_a > I_b$). As a result, the polarization bistability (PB) can be observed within the range of $I_a \sim I_b$. In general, the PB may be harmful in some polarization-sensitive systems, but sometimes it may be used to exploit some new application fields.

The influence of optical feedback on the output performances of VCSELs has been studied experimentally and theoretically in recent ten years [1-3]. Of course, Optical feedback can also strongly affect the polarization of VCSEL. Robert *et al.* reported that weak polarization light feedback will affect the polarization conversion of VCSELs in a short external cavity [4]. Hong *et al.* experimentally and theoretically demonstrated that optical feedback can influence the PB of VCSELs [5]. However, we have noticed that most of relavant theoretical investigations usually adopt single trip optical feedback approximation for simplification. Though this treatment can explain some physical processes to a certain degree, the error is inevitable due to the fact that the multiple trip feedback uaually exists. In previous papers the influence of the residual Fabry-Pérot cavity mode on the non-degenerated four-wave missing in a DFB laser has been investigated [18], as well as the synchronized characteristics of the incoherent optical feedback chaotic system [19]. In this paper, based on a modified model including multiple trip optical feedbacks, the polarization performances of VCSEL subject to optical feedback have been investigated, and the obtained results have been compared with those obtained by the single trip approximation.

2. Theoretical model

System configuration used to study PB in optical feedback VCSEL is shown in Fig. 1. The VCSEL output is divided into two paths using a beam splitter (BS). One path of the laser output beam is reflected by the external cavity mirror (M1), where one part of the reflected light directly enters into VCSEL and forms the first order external cavity feedback. The other part of reflective beam is reflected back to M1 by top layer of VCSEL and forms the second feedback. Repeating such processes, the multiple trip feedbacks can be formed. The other path of the laser output beam transmits through a half wave plate (HWP) and enters a polarization beam splitter (PBS). Finally, the Y-polarization part and X-polarization part are injected separately the photoelectric detectors PD1 and PD2. In this configuration, neutral density filter (NDF) can be used to control the feedback intensity, and the optical isolators (ISO1 and ISO2) are used to prevent light feedback from the detectors into the VCSEL.

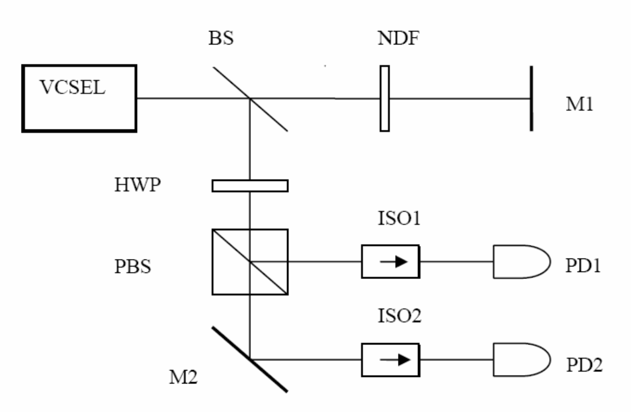

Fig. 1. System configuration used to study PB in optical feedback VCSEL. BS: Beam splitter; NDF: Neutral density filter; HWP: Half wave plate; PBS: Polarization beam splitter; M1: External mirror; ISO: Optical isolators; PD: Optoelectronic detector.

M2: Mirror.

Considering the multiple trip optical feedbacks, the dynamics of VCSELs subject to optical feedback can be described by the following rate equations [3], [5], [7]

$$\frac{dE_x}{dt} = \frac{1}{2}(1+i\alpha)(\Gamma_x G_x - \gamma_x)E_x(t) + \sum_{m=1}^{\infty} \kappa_{xm} E_x(t-m\tau)\exp(-i\omega_x m\tau) \tag{1}$$

$$\frac{dE_y}{dt} = \frac{1}{2}(1+i\alpha)(\Gamma_y G_y - \gamma_y)E_y(t) + \sum_{m=1}^{\infty} \kappa_{ym} E_y(t-m\tau)\exp(-i\omega_y m\tau) \tag{2}$$

$$\frac{dN}{dt} = \frac{I}{eV} - \frac{N}{\tau_s} - G_x\left|E_x\right|^2 - G_y\left|E_y\right|^2 \tag{3}$$

$$G_{x,y} = g_{x,y}(N - N_0)(1 - \varepsilon^s_{x,y}\left|E_{x,y}\right|^2 - \varepsilon^c_{x,y}\left|E_{y,x}\right|^2) \tag{4}$$

where E is the slowly varying electric field of VCSEL, the subscripts x and y denote X-polarization and Y-polarization, respectively, m is the order number of optical feedback, N is the time dependent carrier density, N_0 is the transparency carrier density, α is line-width broadening factor, Γ is the confinement factor, τ is the feedback delay time, $\gamma=1/\tau_p$, where τ_p is the photon lifetime, τ_s is the carrier lifetime, ω is the optical frequency, I is the bias current, V is the volume of the active region, g is the gain coefficient, where $g_x=g_y+g_0(1-I/I_0)$ (I_0 is the switching current in the absence of self-gain and cross-gain suppressions, $I_o=1.4I_{th}$ [6] and I_{th} is the threshold current), ε^s is self-gain saturation coefficient, ε^c is cross-gain saturation coefficient. The inclusion of self-gain and cross-gain saturation introduces hysteresis into the polarization resolved P-I characteristics. The research indicated that the exact location of the polarization switching points is controlled by three factors, i. e., net gain $\Delta G = (\Gamma_x G_x - \gamma_x) - (\Gamma_y G_y - \gamma_y)$, E-field (via the gain saturation) and the injection current, and the nonlinear relationship between these three factors causes the P-I hysteresis [5]. k_m is the optical feedback rate and can be written as [3],[5]

$$\kappa_{ym} = \frac{1-R_2}{\tau_{in} R_2}(R_3 R_2)^{m/2} \tag{5}$$

where R_2 is the facet reflectivity of VCSEL, R_3 is power reflectivity of an external mirror, m is the order of the external cavity feedback, τ_{in} is the internal roundtrip, and $k_{xm}=0.9k_{ym}$[5].

3. Results and discussion

The rate equations (1)-(3) can be numerically solved by fourth-order Runge-Kutta method. During the calculations, the used data of parameters are [1]: $g_0=5.0\times10^{-13}$ m^{3}s^{-1}, $g_y=2.0\times10^{-12}$ m^{3}s^{-1}, I_{th}=12mA, $I_0=1.4$ I_{th}, $\varepsilon^s_x=2\times10^{-23}$ m^3, $\varepsilon^c_x=4\times10^{-23}$ m^3, $\varepsilon^s_y=2\times10^{-23}$ m^3, $\varepsilon^c_y=4\times10^{-23}$ m^3, τ_s=2ns, τ=2ns, $\tau_{in}=1.4\times10^{-5}$ ns, V=5.1×10^{-17}m^3, $\alpha=3$, $\omega_x=6.16\times10^{14}$, $\omega_y=6.1566\times10^{14}$, $N_0=2.5\times10^{24}$ m^3, $R_2=0.995$, τ_{px}=3.0ps, τ_{py}=3.2ps, $\Gamma_x=0.4$, $\Gamma_y=0.35$.

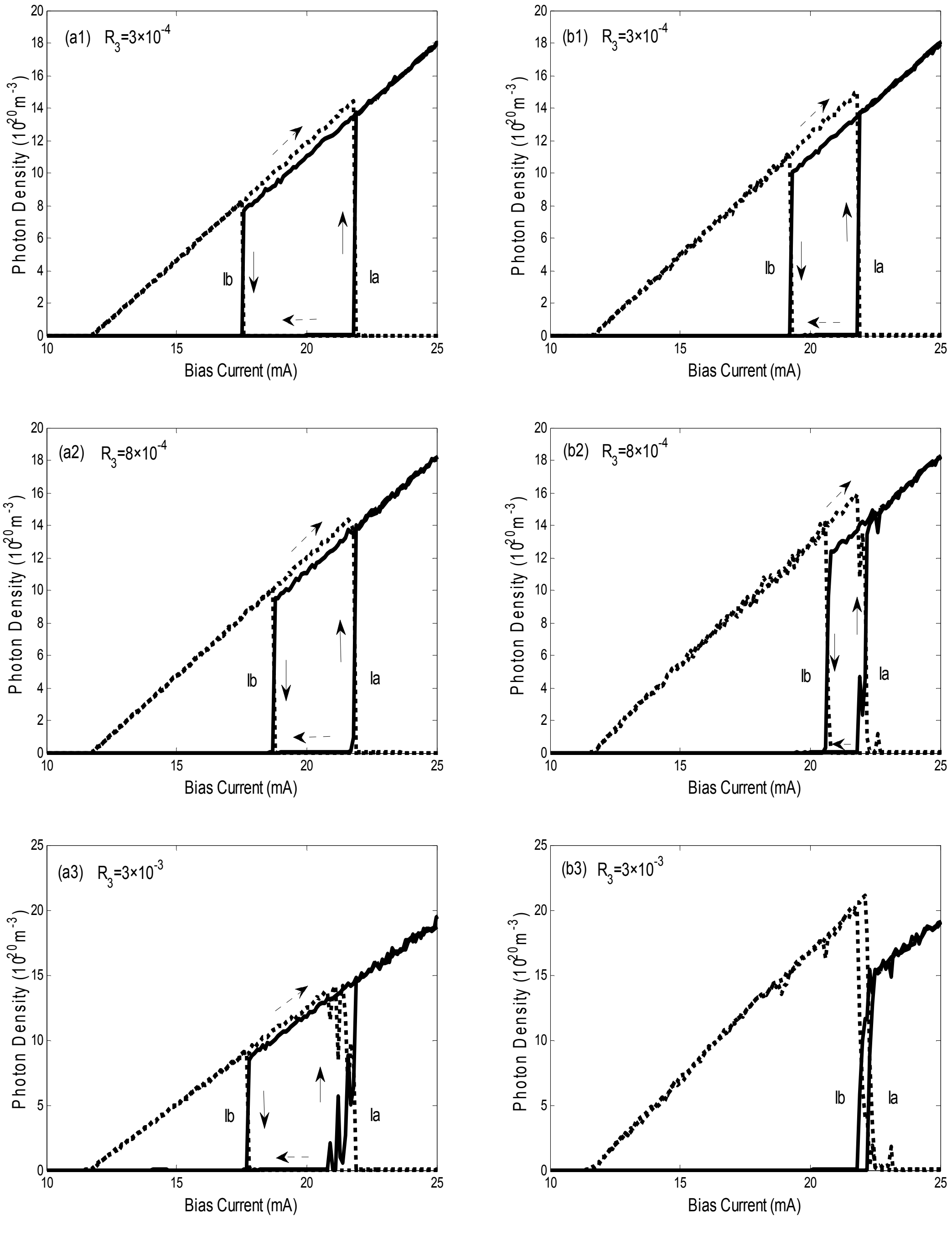

Fig. 2. P-I curve of the VCSEL with different R_3. Left volume: single trip optical feedback; Right volume: multiple trip optical feedback; Solid line: y-polarization mode; Dashed line: x-polarization mode.

The P-I curve of the VCSEL with different R_3 is shown in Fig. 2. For $R_3=3\times10^{-4}$ (see figs. a1 and b1), it can be seen that, for single trip feedback approximation or multiple trip feedback, only one polarization switching (PS) point I_a occurs during increasing the bias current, and only one PS point I_b occurs during decreasing the bias current. So the PB can be observed clearly within the biased current range of I_a~I_b. However, compared multiple trip feedbacks (see fig. b1) with single trip approximation (see fig. a1), I_b increases and the hysteresis loop width decreases after using multiple trip approximation. For $R_3=8\times10^{-4}$ (see figs. a2 and b2), under single trip approximation, only one PS point I_a occurs during bias current increasing and only one PS point I_b occurs during bias current decreasing. However, under the multiple trip feedbacks case, two PS points appear during the bias current increasing. So the structure of the hysteresis loop becomes more complex than that obtained by the single trip feedback approximation. Further more, compared with single trip approximation, the PS point I_b of multiple trip feedbacks increases and the hysteresis loop width decreases also. For $R_3=3\times10^{-3}$ (see figs. a3 and b3), compared with the lower value R_3, the number of PS point increases and the structure of the hysteresis loop becomes more complex for both single trip feedback approximation and multiple trip feedback. But for the multiple trip feedback, the hysteresis loop width decreases seriously.

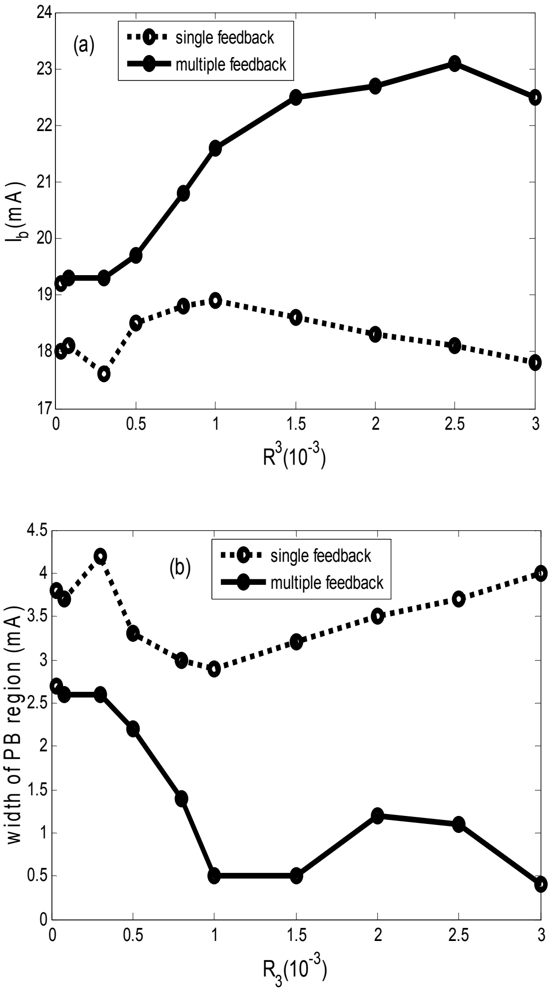

Fig. 3. (a) I_b values for different external mirror reflectivity R_3. (b) Widths of the PB regions for different external mirror reflectivity R_3. Solid line: multiple trip optical feedback; Dashed line: single trip optical feedback approximation.

Fig. 3(a) show I_b values for different external mirror reflectivity R_3. From this diagram, it can be seen that with the increase of R_3, the PS point I_b increases obviously under the multiple trip feedbacks but undergoes a slow reduction tendency with the single trip optical feedback approximation. Fig. 3(b) plots the PB region widths for different R_3 values. It can be seen that with the increase of R_3, the width increases slowly using the single trip optical feedback approximation, but it decreases severely after adopting the multiple trip optical feedbacks. Although some fluctuations exist, the overall tendency is clear. With the increase of external mirror reflectivity R_3, the difference between the single trip approximation and the multiple trip feedbacks become more and more significant, and even the variation tendency for the PB region width is totally different. Therefore, the consideration of the multiple trip feedback is very necessary for accurately analyzing the PB property of VCSEL, especially for the high external mirror reflectivity

4. Conclusions

In this paper, based on system model of VCSEL with optical feedback, the corresponding rate equations with polarization bistability have been established after considering the VCSEL subject to multiple trip optical feedbacks. Compared the results obtain by multiple trip feedbacks with those obtained by single trip approximation, the differences of the basic characteristics of polarization bistability such as switch-on current I_a, switch-off current I_b and hysteresis loop can be observed. With the increase of external mirror reflectivity R_3, the difference obtained by this two approaches become more and more significant. Under certain condition, even the variation tendency for the PB region width by these two methods is totally different. Therefore, in order to accurately model the PB performance in VCSELs subject to optical feedback, the multiple trip optical feedbacks should be taken into account.

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