Quantum dot spin-V(E)CSELs: polarization switching and periodic oscillations

Nianqiang Li
Dimitris Alexandropoulos
Hadi Susanto
Ian Henning
Michael Adams
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ABSTRACT

Spin-polarized vertical (external) cavity surface-emitting lasers [Spin-V(E)CSELs] using quantum dot (QD) material for the active region, can display polarization switching between the right- and left-circularly polarized fields via control of the pump polarization. In particular, our previous experimental results have shown that the output polarization ellipticity of the spin-V(E)CSEL emission can exhibit either the same handedness as that of the pump polarization or the opposite, depending on the experimental operating conditions. In this contribution, we use a modified version of the spin-flip model in conjunction with combined time-independent stability analysis and direct time integration. With two representative sets of parameters our simulation results show good agreement with experimental observations. In addition periodic oscillations provide further insight into the dynamic properties of spin-V(E)CSELs.

Keywords: Spin-V(E)CSELs, polarization switching, periodic oscillations

1. INTRODUCTION

In recent years, considerable attention has been devoted to the control of the output polarization in spin-polarized lasers. Both electrical injection with magnetic contacts, and optical pumping have been employed for the injection of spin-polarized carriers where the latter has shown that the output polarization of the spin-polarized devices can be readily varied by that of the pump. In particular the study of carrier spin in vertical cavity lasers surface emitting lasers (spin-VCSELs) has received experimental and theoretical attention due to advantages such as low threshold and the potential for high-speed operation.

Most spin-VCSEL research to date has been focused on quantum well (QW) active materials, although advances in materials technology have led to an important line of research into quantum dot (QD) based light sources. There have been a number of reports on QD spin-VCSELs, and most recently our group has reported the first QD spin-Vertical external Cavity Surface Emitting Laser (VECSEL), operating at room temperature and at the 1300nm telecom wavelength. In this work our experimental observations have shown that the output polarization ellipticity of the spin-VECSEL emission can exhibit either the same handedness as that of the pump polarization or the opposite, depending on the experimental operating conditions. In addition, in related theoretical work, a modified version of spin-flip model has been used in order to study the static and dynamical properties in QD spin-V(E)CSELs. Interesting phenomena including polarization switching between right- and left-circularly polarized (RCP and LCP) fields and periodic oscillations, have been predicted by numerical simulations. In order to understand the mechanism, a stability analysis of QD spin-V(E)CSELs has also been carried out, revealing that the polarization switching occurs between two possible sets of solutions as the pump intensity or polarization is varied; these were referred to as in-phase and out-of-phase solutions. However, the two polarization switching scenarios observed in the previous experiments mentioned above, i.e., Figs. 4 and 5 shown in Ref. 13, have not been studied using this model of QD spin-V(E)CSELs.

Thus in this paper, we focus our attention on the switching behavior of QD spin-V(E)CSELs under continuous-wave optical pumping in a stable operating region. We find that when the pump polarization is changed from LCP to RCP, *Corresponding author. Email address: adamm@essex.ac.uk

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a switch in emission from LCP to RCP or from RCP to LCP occurs, in agreement with previous experimental observations. In regions exhibiting temporal instability, some examples of periodic oscillations will also be given, which gives insight for high-frequency related applications.

2. THEORETICAL MODEL

Our QD spin-V(E)CSEL model has been described in detail in previous publications and hence only a brief description is given here. In the model there are six variables, the normalized complex electric fields denoted by \( E_+ \) (for RCP), normalized conduction band carrier concentrations \( n \) with subscripts WL (wetting layer) and QD (quantum dot ground state), each with superscripts + for spin-down and – for spin-up. In the model we assume that spin relaxation of carriers within the WL and the QD occurs at the same rate \( \gamma \), that the carrier capture rate from WL to QD is denoted by \( \gamma_o \), and that the polarized fields are coupled by the birefringence rate \( \gamma_p \) and also by the dichroism (gain anisotropy) \( \gamma_a \). We also assume that recombination of carriers in the WL can be neglected and thus capture into the ground state of the QD is the dominant process; effects of excited states in the QD are not included, nor are escape of carriers from the QD back to the WL; Pauli blocking of carriers pumped into the WL is neglected, but the blocking effect of capture into the QD is included.

To facilitate our simulations, we express the complex-valued electric fields of RCP and LCP, \( E_+ \) and \( E_- \), in terms of amplitudes and phases:

\[
E_+ = R e^{i\varphi_a}, \quad E_- = R e^{i\varphi_R}, \quad \varphi_R = \varphi_a - \varphi_A
\]

Substituting these into the rate equations in Ref. 16, we obtain the following equations:

\[
\begin{align*}
\frac{dR_A}{dt} &= \kappa(n_{q0} - 1)R_A - (\gamma_a \cos \varphi_{R \downarrow} - \gamma_p \sin \varphi_{R \downarrow})R_B \\
\frac{dR_B}{dt} &= \kappa(n_{q0} - 1)R_B - (\gamma_a \cos \varphi_{R \downarrow} + \gamma_p \sin \varphi_{R \downarrow})R_A \\
\frac{d\varphi_{R \downarrow}}{dt} &= \kappa\alpha(n_{q0} - n_{q0}^+) + \frac{R_A}{R_B} + \frac{R_B}{R_A} r_a \sin \varphi_{R \downarrow} - \frac{R_A}{R_B} - \frac{R_B}{R_A} r_p \cos \varphi_{R \downarrow} \\
\frac{dn_{RL}^+}{dt} &= \eta_n^+ \gamma_a + h \gamma_n a R_{RL}^+ \left[ \frac{h - n_{q0}^+}{2h} \right] + \gamma_j(n_{RL}^+ - n_{RL}^-) \\
\frac{dn_{RL}^-}{dt} &= \gamma_n^+ n_{RL}^- (h - n_{q0}^+) - \gamma_n (h + n_{q0}^+) \mp \gamma_j(n_{q0}^+ - n_{q0}^-) - 2\gamma_n^+ n_{q0}^+ R_{A,B}^2
\end{align*}
\]

where \( R_A \) and \( R_B \) are amplitudes of RCP and LCP, respectively, \( \varphi_A \) and \( \varphi_R \) are the corresponding phases (\( \varphi_{R \downarrow} \) is the phase difference). \( \kappa \) is the photon decay rate, \( \alpha \) is the linewidth enhancement factor, \( \eta_n \) (\( \eta_a \)) is the RCP(LCP) component of the pump and \( \gamma_a \) is the recombination rate of carriers from the QD ground state. The parameters \( \gamma_a, \gamma_p, \gamma_A, \gamma_R, \) and \( \kappa \) have dimensions of inverse time and the parameter \( \alpha \) is dimensionless. The dimensionless parameter \( h \) is a normalized gain coefficient that is given by equation (4) in Ref. 16.

Equations (1)-(5) have been solved using fourth-order Runge-Kutta algorithm and the corresponding steady-state solutions have been obtained by employing the Newton-Raphson method. In the following, we will consider two important control parameters, i.e., pump intensity \( \eta \) and pump polarization \( P \), and present the numerical results for the circularly polarised output intensity \( |E_\pm|^2 \), the total output intensity \( I \), and the output polarization \( \varepsilon \). They are defined as...
\[ \eta = \eta_+ + \eta_-, \quad P = \frac{\eta_+ - \eta_-}{\eta_+ + \eta_-}, \quad I = |E_1|^2 + |E_2|^2, \quad \varepsilon = \frac{|E_1|^2 - |E_2|^2}{|E_1|^2 + |E_2|^2} \]

where values of \( P \) or \( \varepsilon \) of +1 (-1) correspond to RCP (LCP), whereas a value of 0 corresponds to linear polarization. Note that in our simulations we consider two sets of model parameter values, as given in Table 1, denoted VCSEL1 and VCSEL2. These were chosen in the light of previous experimental observations where we found that these two sets of parameters provide close agreement between theory and a range of experimental observations.

**Table 1. Values of parameters for two examples of QD spin-V(E)CSELs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>VCSEL1 value</th>
<th>VCSEL2 value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon decay rate</td>
<td>( \kappa )</td>
<td>250 ns(^{-1} )</td>
<td>250 ns(^{-1} )</td>
</tr>
<tr>
<td>Carrier recombination rate</td>
<td>( \gamma_\alpha )</td>
<td>1 ns(^{-1} )</td>
<td>1 ns(^{-1} )</td>
</tr>
<tr>
<td>Capture rate into WL into QD</td>
<td>( \gamma_o )</td>
<td>400 ns(^{-1} )</td>
<td>400 ns(^{-1} )</td>
</tr>
<tr>
<td>Spin relaxation rate</td>
<td>( \gamma_j )</td>
<td>10 ns(^{-1} )</td>
<td>1 ns(^{-1} )</td>
</tr>
<tr>
<td>Birefringence rate</td>
<td>( \gamma_p )</td>
<td>20 ns(^{-1} )</td>
<td>40 ns(^{-1} )</td>
</tr>
<tr>
<td>Dichroism rate</td>
<td>( \gamma_a )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Linewidth enhancement factor</td>
<td>( \alpha )</td>
<td>4</td>
<td>0.4</td>
</tr>
<tr>
<td>Normalized gain coefficient</td>
<td>( h )</td>
<td>1.05</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 1. VCSEL1: Output polarization \( \varepsilon \) as a function of the pump polarization \( P \) for four cases of the pump intensity \( \eta \): (a1) \( \eta = 1.3 \), (b1) \( \eta = 1.4 \), (c1) \( \eta = 1.7 \), and (d1) \( \eta = 1.9 \). The corresponding real parts of the critical eigenvalue are shown in (a2)-(d2).

3. RESULTS

Figures 1(a1)-(d1) shows the output polarization \( \varepsilon \) as a function of the pump polarization \( P \) for different values of the pump intensity \( \eta \) in VCSEL 1: (a1) \( \eta = 1.3 \), (b1) \( \eta = 1.4 \), (c1) \( \eta = 1.7 \), and (d1) \( \eta = 1.9 \). As expected, one can see that the output polarization can be switched by controlling the pump polarization. More importantly, it is clearly observed that the output polarization follows that of the pump, but with the opposite sign, which is consistent with the
experimental observation for the QD spin-V(E)CSEL shown in Fig. 4 of Ref. 13. Our stability analysis indicates that in all cases, the in-phase stationary solutions are always selected, while the out-of-phase ones are unstable. This is confirmed by the sign of the real parts of the critical eigenvalue shown in Figs. 1(a2)-d(d2). This means that this polarization switching scenario is determined by the in-phase solutions.

In order to gain more insight into the dynamics of VCSEL1, we calculate the output intensity $I$ and the output polarization $\varepsilon$ in the plane of the pump intensity $\eta$ and polarization $P$. The results are shown in Fig. 2. It should be noted that only the results for the stable region are indicated in the color maps. As can be seen from this figure, the stable results shown in Fig. 1 can be guaranteed in the whole range of polarization $P$, provided that the pump intensity $\eta$ is not greater than 2. When $\eta \geq 2$, a large region of instability is found, where periodic oscillations are possible.

Now we focus on VCSEL2 and carry out the same analysis as that for VCSEL1. The results are shown in Figs. 3 and 4. In Figs. 3 (a1)-(d1), the output polarization $\varepsilon$ as a function of the pump polarization $P$ is displayed for different values of the pump intensity $\eta$ in VCSEL 2: (a1) $\eta = 1.4$, (b1) $\eta = 1.5$, (c1) $\eta = 1.6$, and (d1) $\eta = 1.7$. The corresponding real parts of the critical eigenvalue are shown in (a2)-(d2).

Contrary to VCSEL1, the output polarization of VCSEL2 follows that of the pump with the same sign, which agrees with the experimental observation shown in Fig. 5 of Ref. 13 and other previous reports. This type of polarization switching is determined by the out-of-phase solutions. As shown in Figs. 3(a2)-(d2) the real parts of the out-of-phase solutions are negative in
almost the whole range of polarization \( P \). In fact, one can see a kink around \( P = 0 \) for the chosen \( \eta \) because of VCSEL2’s unstable behavior for a small interval of \( P \). Figure 4 depicts the calculated maps of the output intensity \( I \) and the output polarization \( \varepsilon \) in the plane of the pump intensity \( \eta \) and polarization \( P \). These results confirm the unstable behavior found in VCSEL2 and clearly show that the region of instability becomes slightly wider as \( \eta \) is increased progressively.

Figure 4. VCSEL2: calculated maps of (a) the total output intensity \( I \) and (b) the output polarization \( \varepsilon \) in the plane of the pump intensity \( \eta \) and polarization \( P \).

It should be noted that the two switching scenarios resemble a monotonic increase or decrease in \( \varepsilon \) as \( P \) is increased from -1 (LCP) to 1 (RCP). However, in some other cases, one can see a mixture of these two scenarios as the pump polarization is varied. This has been observed in some previous work. Finally, we present some examples of periodic oscillations that may occur in the unstable region both for VCSEL1 and VCSEL2. It is well known that the frequency of oscillations in spin-V(E)CSEL can be determined by the birefringence rate, rather than the relaxation oscillation frequency (ROF). Here we consider two pump levels, i.e., \( \eta = 2.5 \) and 4. For the parameter sets in VCSEL1 and VCSEL2, the ROF is given by \( \frac{1}{2} \left[ 2 \kappa \gamma (\eta - 1) \right]^{1/2}/(2\pi) \), which yields 4.4 GHz and 6.2 GHz for \( \eta = 2.5 \) and 4, respectively. Figure 5 shows the intensity time series and corresponding power spectra of antiphase periodic oscillations in the RCP and LCP of VCSEL1, for \( P = 0.7 \) and two values of \( \eta \) as mentioned above. The frequency of oscillation for these examples is about 6.6 GHz (determined by birefringence \( \gamma_p/\pi \approx 6.4 \) GHz in VCSEL1), almost independent of \( \eta \). Likewise, Fig. 6 presents the oscillations in VCSEL2 for \( P = 0.1 \) and these two
values of $\eta$. The frequency of oscillation for these examples is about 13.2 GHz. For comparison the frequency corresponding to the birefringence for VCSEL2 is given approximately by $\gamma_p/\pi = 12.7$ GHz.

![Graph](image)

Figure 6. Periodic oscillations in VCSEL2. (a,c) RCP and LCP intensity time series and (b,d) the corresponding power spectra. (a,b) $P = 0.1$ and $\eta = 2.5$, and (c,d) $P = 0.1$ and $\eta = 4$.

4. CONCLUSION

In conclusion, we report two polarization switching scenarios in spin-V(E)CSELs based on the modified version of spin-flip model, that is, the output polarization ellipticity of the spin-V(E)CSEL emission can exhibit either the same handedness as that of the pump polarization or the opposite. Our simulations agree well with previous experiments and explain the reason why different switching responses can occur through controlling the pump polarization. Additionally, some examples of antiphase periodic oscillations governed by birefringence are presented.

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REFERENCES


