Abstract—In this paper, the influence of variable-angle polarization-rotated optical feedback on the polarization switching properties of vertical-cavity surface-emitting lasers (VCSELs) is investigated theoretically and experimentally. The optical feedback (OF) level and the rotated polarization angle $\theta_p$ of OF are considered. Two configurations of OF are used to re-injected parallel and orthogonal polarization modes back into the VCSEL. For the parallel OF, it is shown that polarization switching (PS) of VCSELs’ modes can occur at a fixed feedback level and bias current with variable polarization switching (PS) of VCSELs’ modes can occur at a fixed feedback level and bias current with variable $\theta_p$, particularly when the intensities of two polarization modes become comparable with each other. In the theoretical model for both OF conditions, there is good agreement between the experimental measurements and recent theoretical results reported in the literature.

Index Terms—Vertical-cavity surface emitting lasers (VCSELs), variable polarization angle, optical feedback, polarization switching (PS).

I. INTRODUCTION

VERTICAL-CAVITY surface-emitting lasers (VCSELs) are attractive light sources because of their desirable characteristics, such as a low threshold current, single-longitudinal operation and circular output-beam profile, which make VCSELs promising devices in many applications [1]–[4]. However, VCSELs are very sensitive to the optical feedback (OF) because of their short cavity length and a large emitting area. Several theoretical and experimental studies have been made to study the polarization properties of VCSELs under different OF conditions [5]–[9]. OF strongly affects the dynamics of VCSEL devices, and has been the subject of extensive research activities in recent years. However, the majority of previous studies have focused on the influence of conventional OF on the dynamical characteristics and stability of the VCSELs [5], [10]–[12]. The VCSELs spectral characteristics and their controllable polarization switching (PS) characteristics have also been investigated [13]–[16].

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free data transmission can be achieved with higher polarization stability [26].

The remainder of this paper is organized as follows; In section II the experimental setups details are given. In section III, results and discussion are presented, which contains the polarization resolved light-current (L-I) characteristics of free-running VCSEL, as well as the effect of OF level and variable polarization angle. In section IV, the numerical results of configurations A and B are given. Finally, in section V, brief conclusions are made.

II. EXPERIMENTAL ARRANGEMENT

Here two different OF configurations were considered: A and B, which are illustrated in Figs. 1(a) and (b), respectively. A premium 850 nm single mode VCSEL (Avalon photonics UK Components Ltd) with a threshold current of 3.9 mA and a side-mode suppression ratio (SMR) >33dB was used. The VCSEL was driven by a DC source (7651 YOKOGAWA) and was temperature controlled using a thermoelectric temperature controller (TED 200) to within 0.01 °C. With regards to the configuration A, a half wave plate (HWP 1) was used to select the polarization direction of VCSEL’s mode (XP), and an isolator (ISO) with an attenuation >40 dB was utilised to ensure that the beam from the VCSEL passed though the OF loop in one direction, and then was re-injected back into the VCSEL. The HWP2 was used to rotate the polarization direction from 0° (maximum power passed through HWP2) to 90° at a rotating increment angle of 5°. The OF level was adjusted using a neutral density filter (NDF). The power meter (PM) was used to measure the OF level. The laser output power was measured using two photo-detectors (PD1, PD2) via HWP3 and a polarization beam splitter (PBS). The detectors (Newport model AD-70xr) used have a 6 GHz bandwidth.

III. RESULTS AND DISCUSSION

A. The Effect of Optical Feedback Level

Fig. 2 displays the polarization resolved L-I characteristics of the free-running VCSEL. The VCSEL starts to lase at a threshold current of ≈3.9 mA with XP (black curve) and YP (red curve) modes being the dominant and suppressed modes, respectively. No PS was observed in the entire range of the bias current $I_B$. Note that, $I_B$ was fixed at 6 mA (i.e., mid-point of the L-I curve) for all the experiments with results depicted in Figs. (3-7). In this way, it was ensured that the YP mode was significantly suppressed relative to the XP mode.

In this work the OF level was defined as the ratio of the feedback power (measured at BS2 and BS for configurations A and B, respectively) to the total VCSEL output power.  
1) Case A: First, consideration was given to study the polarization properties of VCSEL at $\theta_p = 0^\circ$ (i.e., parallel OF (XP) to the solitary VCSEL mode). Figure 3(a) shows that for $\theta_p = 0^\circ$ VCSEL emits a single XP mode over the entire range of OF level. This is because at $\theta_p = 0^\circ$ the XP mode will attain all the OF light. In Fig. 3(b) for $\theta_p = 45^\circ$, the intensities of both modes increase with the XP mode remaining the dominant mode. In this case, the OF was shared equally between the XP and YP modes. For $\theta_p > 45^\circ$, the intensities of the XP and YP modes decrease and increase, respectively. In this case the XP (YP) mode loses (gains) the OF light over the range of the OF. In addition, for $\theta_p > 45^\circ$ it can be noted from Figs. 3(c, d) that both XP and YP intensities are close to each other, which leads to PS occurring at higher OF levels (i.e., -14 dB). In this case, in contrast to the XP mode, the YP mode experiences more OF light with increased $\theta_p$.

2) Case B: The intensities of the XP and YP modes versus the OF level for the configuration B are shown in Fig. 4. For $\theta_p = 0^\circ$ as in Fig 4(a), VCSEL exhibits a single polarization mode (XP), as in Fig. 3(a). The XP mode is the dominant mode even when it is subjected to a strong OF level. Note that, $I_B$ was fixed at a value to ensure that the YP mode was highly
suppressed, so no light was reflected to the YP mode (i.e., zero feedback). In Fig. 4(b) both intensities of XP and YP mode exhibit similar behaviour, gradually increasing with the OF level. At $\theta_p$ of 45°, both modes are subjected to an equal OF level. Furthermore, as $\theta_p$ increases the XP (YP) mode loses (obtains) more OF light. At the comparable feedback strength level both XP and YP have almost the same intensities behaviours.

Fig. 4(c, d), illustrate further enhancement of the YP mode as well as the total intensity, whilst the XP mode intensity decreases slightly, with increasing OF level over the entire range for $\theta_p = 75°$ and 90°. For the configuration B and over the entire range of OF, the XP mode is always the dominant mode for all values of $\theta_p$, and with no PS, as was theoretically predicted in [22]. This is mainly attributed to the gain of the YP mode being less than the gain of the XP mode, (see Fig. 7)

B. The Effects of Variable Polarization Angle

Next, the effects of varying $\theta_p$ of OF on the PS of VCSEL are considered. In this case, both the OF level and $I_B$ were fixed and $\theta_p$ was varied from 0° to 90°.

1) Case A: For the configuration A, the polarization-resolved intensities as a function of $\theta_p$ are shown in Fig. 5 for a range of OF levels at $-15.6$, $-15$, $-14$, and $-13$ dB. Fig. 5 shows that the XP (YP) mode decreases (increases) gradually with increasing $\theta_p$. Moreover, higher levels of OF lead to PS between VCSEL’s modes, as shown in Figs. 5(c) and (d). The PS position is dependent on the OF level and $\theta_p$, where a smaller $\theta_p$ is required to implement PS when the OF level increases.

As a result, the total emission intensity began to decreases when $\theta_p$ increase. The results illustrate that a smaller polarization angle is required to realize PS when the OF level increases. The experimental results are in good agreement with the previous theoretical analysis [22], which predicted that for a relatively larger feedback level the OF and the gain compete for the dominant effect.

2) Case B: For the configuration B, the polarization resolved output intensities as a function of $\theta_p$ dependant on the OF level are displayed in Fig. 6. It can be observed from Fig. 6 that as $\theta_p$ increases over a range of $0° \leq \theta_p \leq 20°$, the intensity of the XP mode decreases, whilst that of the YP mode increases.

Furthermore, increasing $\theta_p$ beyond 20° leads to the decrease in the intensity of the XP mode and the total intensity.
However, when the feedback level increases the polarization properties are different than the case with lower feedback levels. For the feedback levels of -7.5 dB and -6 dB, PS occurs and its location is based on the OF level. At a feedback level of -7.5 dB PS is located at $\theta_p$ of about 76°, see Fig. 6(c), which moves down to 74° at an OF level of -6 dB as in Fig. 6(d). This illustrates that VCSEL with a higher feedback level requires a smaller $\theta_p$ to achieve PS.

Further explanation for above results in Fig. 6 can be obtained via consideration of the feedback effects on the XP and YP modes as in Fig. 7. The feedback intensities of the XP and YP modes have sinusoidal dependency on $\theta_p$ as illustrated in Fig. 7. The feedback intensities of the XP and YP modes are comparable with the corresponding experimental measurements. PS occurs for $\theta_p = 22$°, and $\theta_p = 30$°, which is the same point as demonstrated in practical measurements. PS occurs at the OF coefficient of 22 ns$^{-1}$, which is the same point as in practical measurements, see Fig. 3(d). Furthermore, for the configuration A, Fig. 9 shows the numerical results of the polarization-resolved intensities of the XP and YP modes as a function of $\theta_p$ when the VCSEL is subjected to different OF levels. It is shown that, for the OF coefficient of 17 ns$^{-1}$ ($\sim -16$ dB) once again the XP and YP are the dominant mode and suppressed modes, respectively.

\[ \frac{dE_x}{dt} = \left(1 + i\alpha\right)\left(N - 1\right)E_x + inE_y - (\gamma_a + i\gamma_p)E_x + \gamma E_x(t - \tau_1)\cos(\theta_p)e^{-i\omega_t} + \sqrt{\beta_p \xi}, \quad (1) \]

\[ \frac{dE_y}{dt} = \left(1 + i\alpha\right)\left(N - 1\right)E_y - inE_x + (\gamma_a + i\gamma_p)E_y + \gamma E_y(t - \tau_1)\sin(\theta_p)e^{-i\omega_t} + \sqrt{\beta_p \xi}, \quad (2) \]

\[ \frac{dN}{dt} = \gamma N - N\left(1 + \left|E_x\right|^2 + \left|E_y\right|^2\right) + in(\gamma E_x E_y^* - E_x E_y^*), \quad (3) \]

\[ \frac{dn}{dt} = -\gamma_n n - \gamma N\left(1 + \left|E_x\right|^2 + \left|E_y\right|^2\right) + iN(\gamma E_x E_y^* - E_x E_y^*), \quad (4) \]
Fig. 8. Numerical results of the polarization-resolved intensities of the XP and YP mode with total output intensity as a function of the OF coefficient for $\theta_p$ of: (a) 0°, (b) 45°, (c) 75°, and (d) 90°, for the configuration A model. The squares (circles) line corresponds to the intensity of XP (YP) mode and the green line is the total intensity. The curves for the XP mode and the total output power in (a) are overlapped.

Increasing the feedback level to 24 ns$^{-1}$ ($\sim$ −13 dB) results in PS taking place at $\theta_p$ of $\sim$87°, which is the same angle that was observed in the experimental measurement, see Fig 5. The results illustrate that for the configuration A there is a good agreement between the predicted and measured results, see Figs. 3 and 5.

**B. Numerical Results of Configuration B**

Based on the experimental results shown in Fig. 4 for the configuration B, the predicted results for the XP and YP modes intensities versus the OF level are depicted in Fig. 10. For $\theta_p = 0^\circ$ the XP and YP modes exhibit similar behaviours as in Fig. 4(a). In Fig. 10, for different values of $\theta_p$, the XP is still the dominant mode compared with the entire region of OF coefficient and with no PS being observed. The two polarization modes become close to each other at $\theta_p$ of 90° for OF of 47 ns$^{-1}$ ($\sim$ −7 dB), which is similar to Fig. 4(d).

Fig. 11 presents the numerical measurements of the polarization resolved intensities of the XP and YP modes as a function of $\theta_p$ for OF levels of 20, 30, 45, and 55 ns$^{-1}$ for the configuration B. The corresponding experimental results are illustrated in Fig. 6. Similar tendency of the XP and YP modes in the numeral results can be observed compared to the experimental finding as in Fig. 6. However, PS is observed at slightly different $\theta_p$ of $\sim$ 68°for an OF level of 55 ns$^{-1}$ (−6 dB), which is lower than the experimental result ($\sim$74°).

This is because, for higher levels of OF multiple feedbacks may needed as a part of the theoretical model.

**V. CONCLUSION**

In this study, the effects of the rotated polarization angle $\theta_p$ of the OF on the polarization properties of a VCSEL were investigated theoretically and experimentally. Two different configurations of OF were considered. For the configuration A, the parallel mode (XP mode) was re-injected back into the VCSEL whereas in the configuration B two polarization modes (i.e., XP and YP) were re-injected back into the VCSEL. The results showed that in the configuration A there is a good agreement between measured and predicted results, whereas this was not the case with the configuration B, where it
was observed 6° some difference between experimental and theoretical results for the PS position. This difference can be attributed to multiple OF due to the optical equipment of the setup, which have caused an experimental error. Furthermore, when no PS was observed, the modes intensities were found to be the same at higher OF levels.

The theoretical and experimental measurements of the polarization properties under rotating polarization angle demonstrated that VCSEL with a high OF level will require a smaller \( \theta_p \) to achieve PS. For rotating \( \theta_p \) of the OF VCSEL exhibited PS at a fixed \( I_0 \) and the OF level. Moreover, the experimental measurements demonstrated the theoretical predictions that the larger \( \theta_p \) leads to the PS takes place. Additionally, for higher values of \( \theta_p \) the suppressed mode (YP) is being emitted as in the configuration A. For relatively low levels of OF the polarization modes properties were less affected when changing \( \theta_p \). On the other hand, for the configuration A, the PS was observed when the difference between the feedback strengths of the two modes was high enough.

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**REFERENCES**


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