Polarization output power stabilization of a vertical-cavity surface-emitting laser

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This paper provides an experimental investigation of the polarization stabilization at the output power of an 850 nm vertical-cavity surface-emitting laser (VCSEL) with optical feedback (OF) and a range of polarization angles, OF strength and the bias current. The VCSEL's polarization stabilization is evaluated using the extinction ratio measurements of the optical output power of the polarization modes of the VCSEL. The results clearly show that, rotation of the polarization angle and the OF level can radically change the polarization stabilization of VCSEL. Both the polarization angle and OF introduce polarization switching (PS) and instability in the optical output power of the VCSEL. Consequently, these lead to performance degradation of VCSEL in terms of the operating point and the modulation bandwidth. At a fixed OF level of -7 dB, polarization destabilization is first observed at 450 with the increasing level of polarization angle. Whereas for the fixed polarization angles of 40° and 90°, polarization destabilization is observed at -14.5 dB and -14 dB, respectively with the increasing level of orthogonal OF. We show that, with parallel OF, no PS is observed over the entire OF level. The results also indicate that the VCSEL with no polarization angle requires higher levels of OF in order to ensured PS compared with the case with the polarization angle.

OCIS codes: *(140.3460) Lasers, distributed-feedback; (140.7260) Vertical cavity surface emitting lasers; (190.0190) Nonlinear optics, (250.6715) Switching; (230.0230) Optical devices; (260.5430) Polarization.*

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1. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELs) have become the key elements in short and long-range data networks due to their attractive properties, such as very low threshold current (μA), high modulation bandwidth, low cost and circular output power beam. However, polarization stabilization remains an issue in such devices due to their inherent structures, which leads to the unstable polarization gain [1]. VCSELs generally have a cylindrical symmetric cavity with no flawless or inadequate polarization selectivity. Therefore, it is quite possible to change the polarization direction of a VCSEL [2, 3]. Furthermore, VCSELs are very sensitive to the optical feedback (OF). Polarization switching (PS) between the orthogonally polarization modes of VCSEL can easily occurred with the increasing level of injection current, OF and optical injection [4-6]. However, OF can improve several features of the laser, such as controlling the PS under certain conditions and increasing the side-mode suppression ratio. Note that, VCSELS together with other optical components are used in many application, therefore OF cannot be avoided. Therefore, the stability and sensitivity of VCSELs with OF is a critical issue that need further investigation. In addition it is important to understand the polarization characteristics and behaviour of the VCSEL with the OF effect.

Recently, several theoretical and experimental works have investigated the polarization modes characteristics of VCSELs with either the conventional OF or a rotated polarization angle of OF [5, 7-11]. The dynamics of VCSEL under OF with a rotating polarization angle was shown to have a great potential in numerous applications such as free space optical communications for improved level of security at the physical layer [12-14], sensing [15], high frequency pulses generation and optical bi-stability [16]. However, in some cases, the OF has undesirable effects on the laser characteristics, which can result in unwanted instabilities in the laser output power, thus limiting the laser performance when used for example communication systems. In optical communications the need for light sources with high bandwidth and power stability is paramount, where controlling the polarization state still an issue [17].

This experimental study gives an insight on the influence of the rotating polarization of the OF and the OF strength on the polarization stabilization of the emitted power of the VCSEL. The polarization extinction ratio (EX) measurement has been used to evaluate the modulation amplitude of the VCSEL. The EX, which is an important parameter in intensity modulation of the light source to ensure error-

free data transmission [18], is been used to evaluate polarization stabilization of the VCSEL. Firstly, the orthogonal polarization mode (YP) is selected and re-injected back into the VCSEL with a – 7 dB of OF level. This mode is gradually rotated from 0^0 to 90^0 using a quarter wave plate (QWP). Secondly, the polarization angle is fixed at 0^0 and the OF level is increased from – 21 dB to - 6.5 dB. The measured light-current (L-I) characteristic is monitored using the LabVIEW for data analysis. Note that, the EX is defined as a ratio of the maximum and the minimum output powers of the VCSEL's polarization mode, and the feedback ratio is defined as the ratio of the power fed back into the VCSEL relative to the total output power of the VCSEL at free running operation.

Note that, the polarization behaviours of VCSEL and how it can be controlled when injected with an OF signal is still an ongoing issue, which needs further investigation. In this paper we experimentally investigate the conditions for the OF level and the polarization angle that will ensure stability in the VCSEL. Furthermore, more insight and understanding of the polarization modes behaviours under the OF effect is outlined consideration practical applications of the VCSEL.

2. SETUP DESCRIPTION

The schematic diagram of the experimental setup is shown in Fig. 1. We have used a VCSEL at a wavelength of 850 nm and an output power level of 0.5 mW at a bias current I_B of 8 mA, which is the first transmission window in optical communications mostly used for short range local area networks. The quarter wave plate (QWP) and the neutral density filter (NDF) were used to rotate the polarization angle and control the OF level, respectively. The collimated laser's beam, using a lens located in front of the laser, was reflected back (i.e., OF) into the VCSEL by means of a mirror (M) placed 40 cm away from the VCSEL. Part of the laser beam was directed to a photodetector via a non-polarizer beam splitter (BS) and polarizer (P) for data analysis. An optical power meter was used to measure the output power levels after the P, which does select the polarization state of the XP (parallel polarization mode) and YP modes. Note that, the experiment was carried at the room temperature.

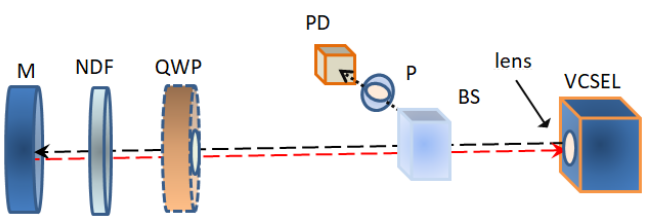

Fig. 1. Feedback scheme for the polarization optical feedback, non-polarizer beam splitter (BS), lens, polarizer (P), photo detector (PD), mirror (M), quarter wave plates (QWP), and neutral density filter (NDF).

3. RESULTS AND DISCUSSION

For the purpose of determining exactly the OF level and the polarization angle, which will destabilized the output power of the VCSEL under the experiment conditions, the polarization resolved L-I curve is measured. The measurements was done by varying the OF level from -21 to -6.5 dB and the polarization angle from 0^0 to 90^0. Note that, the polarization angle of 0^0 refers to the parallel OF, where a maximum light is mainly due to the XP mode. Whiles the polarization angle of 90^0 represents the orthogonal OF light, where the maximum OF light is due to the YP mode. The polarization-resolved L–I curve characteristics for the free running and with the changing polarization angle at a fixed OF level are presented in Fig. 2, where the black and red colors represents the XP and YP modes, respectively. The experimental measurements were carried out at a controlled temperature of 22^0 C.

Figure 2(a) displays the free running L-I curve for the VCSEL with a relatively high side mode suppression ratio (SMSR) of >33 dB and a maximum output power of 0.5mW. Note that, the VCSEL lase with the dominant mode (i.e., XP) at a threshold current of 3.9 mA and with YP mode being suppressed over a range of bias current I_B of 0-9 mA. The influence of the rotating polarization angle on the polarization resolved L-I curve is depicted in Fig. 2(b)-2(-i) for the polarization angle of 0^0 to 90^0 at a fixed OF value of -7 dB. With increasing polarization angle from 0^0, the parallel OF is gradually decreased while the orthogonal OF is increased until 90^0, which represents a maximum light reflected back from the YP mode to the VCSEL.

The results show that for the polarization angles below 45^0 have no effects on the output power of the VCSEL, as demonstrated in the L-I curve measurements in Fig. 2(b)-2(e), where the XP mode increases linearly with the I_B, whereas the YP mode is very low and almost constant. However, for the polarization angle of 45^0 and at I_B of 7.5 mA and 8.6 mA we observe the type I PS (i.e., from the high to the low-frequency polarization) and the type II PS (i.e., from the lower to the higher frequency mode with increasing current), respectively [15], which form a hysteresis in the output power, see Fig. 2(f). As the polarization angle increases beyond 45^0, the PS position slightly moves to the lower I_B and the VCSEL is lasing with the depressed mode. The YP mode is being the dominant mode for $I_B > 6.5$ mA as shown in Fig. 2(g)-2(i). Therefore, the L-I curve characteristics is much different beyond 45^0 compared with the angles below 45^0.

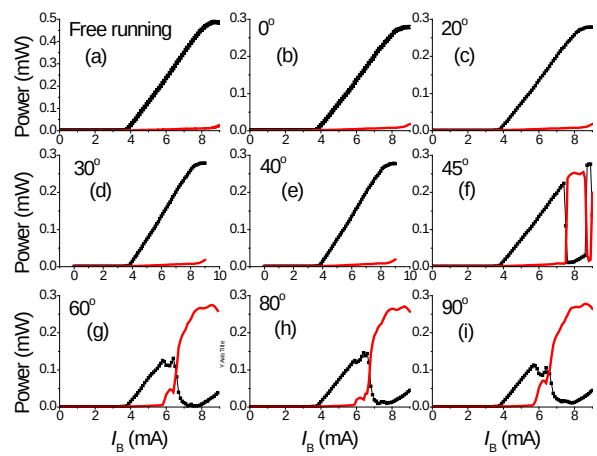

Fig. 2. (a) Characteristics of the free-running, and (b-i) the influence of rotating polarization angle on the polarization resolved light current characteristic (L-I curve) of VCSEL, The black and red colors represents the XP and YP modes.

The corresponding EX measurements of Fig. 2 is displayed in Fig. 3, where the results show how the operation region of the laser is affected by rotating the polarization angle; see the red area in the figure. From the L-I curve the red area displays the operating region above threshold current I_{th} of the laser where the laser polarization power can be modulated.

Beyond the polarization angle of 45^0 the XP mode is no longer valid and the YP mode starts to increase after the PS.

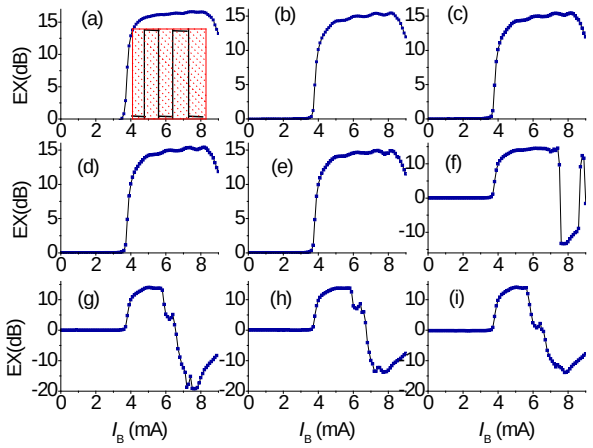

Fig. 3. Corresponding measurements of Fig. 2 of extinction ratio.

The L-I curve characteristics under different OF levels with a polarization angle of 0^0, where parallel OF is applied here, are shown in Fig. 4. Note that, there is no PS over the entire range of OF and I_B. However, increasing the OF level leads to growth of the suppressed mode (i.e., YP) and the depressed XP mode, see Figs. 4(d)-4(f).

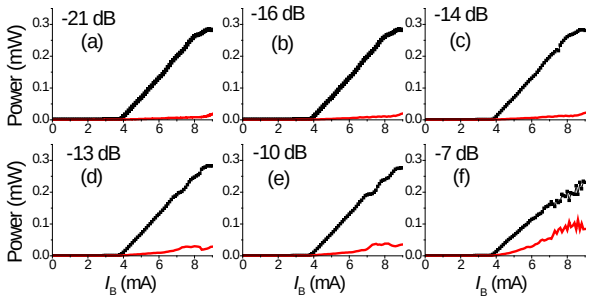

Fig. 4. The influence of OF level with 0^0 of the polarization angle on the polarization resolved light current characteristic (L-I curve) of VCSEL.

The influence of different OF levels as a function of I_B on the polarization resolved L-I characteristic of the VCSEL for a polarization angle of 40^0 is shown in Fig. 5. With regard to the VCSEL's modes behavior, we observe a similar trend to the Fig. 4. However, in Fig. 5 the instability in the output power is observed at the OF level of -14.5 dB. In addition, with the increasing level of OF we observe enhanced modes competition particularly at a OF level of -7 dB as I_B increases. Thus, PS takes place with a lower level of OF when the polarization angle is increased.

Next, the influence of the OF strength on the polarization resolved L-I curve characteristics is shown in Fig. 6. This figure displays the XP and YP modes behavior for a range of OF levels of - 21, -18, -16, -14, -13.5, -11, -7, and - 6.5 dB and for a fixed polarization angle of 90^0. As can be observed from the figure, the OF level of < -14 dB does not have any effect on the L-I curve characteristics of the VCSEL (i.e., the XP and YP modes), see Figs. 6(a-c). Note that, (*i*) the first unstable state of the polarization modes is observed at -14 dB of OF level at I_B of 8.1 mA; and (*ii*) PS beyond the OF level of -14 dB of OF, see Figs. 6(d)-6(h). Note that, increasing the OF level results in PS taking place at lower I_B and with the YP mode being enhanced, which may become the dominant effect compared to the XP mode, see Figs. 6(g) and 6(h).

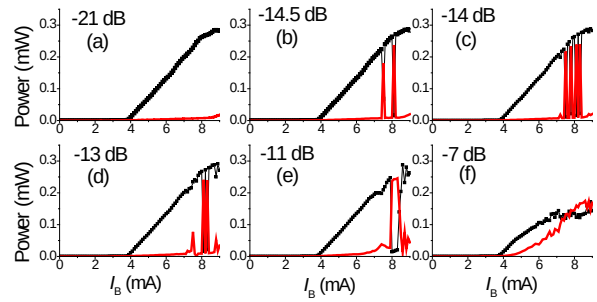

Fig. 5. The influence of OF level with 40^0 of the polarization angle on the polarization resolved light current characteristic (L-I curve) of VCSEL.

The observed modes behavior can be explained by effects of both the gain and the OF strength as outlined in the flowing investigation [5, 9].

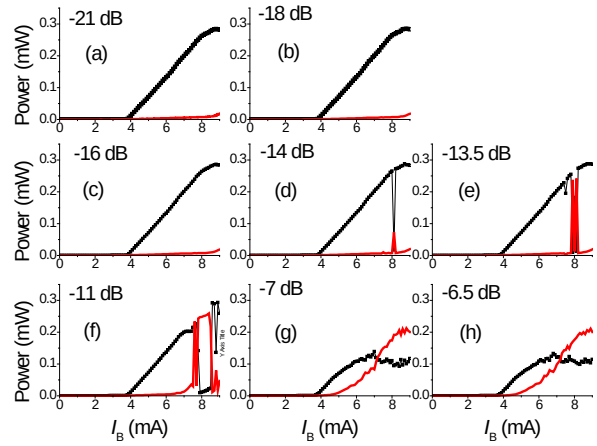

Fig. 6. The influence of the OF level with 90^0 of the polarization angle on the polarization resolved light current characteristic (L-I curve) of VCSEL,

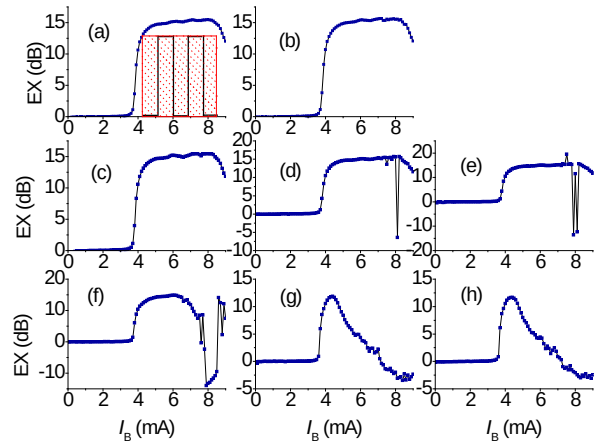

Fig. 7. Corresponding measurements of the extinction ratio.

The corresponding measured EX plots of the L-I curve as a function of I_B for a range of OF levels and for a polarization angle of 90^0 are

presented in Fig. 7. Obviously, increasing of the OF level leads to changes in the operating point and disruption of the modulation bandwidth of the polarization mode of the laser. Further investigation is carried out based on the OF level with the polarization angles of 40^0 and 0^0. To investigate effect of the OF level with no polarization angle, we removed the QWP and measure the L-I response as shown in Fig. 8. Note that, no PS until the OF level is ≥ -11 dB, which is 3 dB higher than Fig. 6. This indicates that the VCSEL with no polarization angle requires a higher level of OF exhibit PS compared with the case with the polarization angle effect.

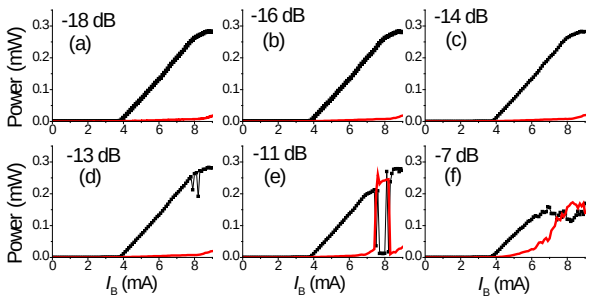

Fig. 8. The influence of the OF level on the polarization resolved light current characteristic (L-I curve) of VCSEL with no polarization angle effect.

The following measurements in Fig. 9 display the output power of the polarization modes, XP and YP, as a function of the polarization angles for a range of I_B of a) 6 mA, b) 6.8 mA and c) 8.5 mA with orthogonal OF, and d) 8.5mA with parallel OF. The OF level was used in Fig. 9 was the maximum optical feedback level of -6 dB

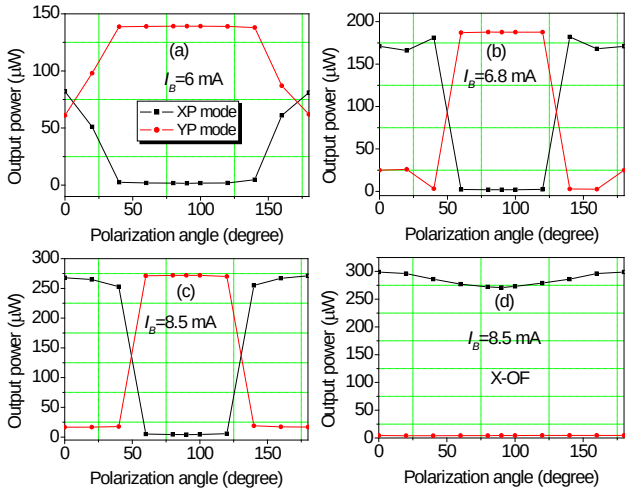

Fig. 9. The output power of the XP and YP modes with orthogonal OF (except (d)) as a function of polarization angles under different IB of: (a) 6 mA, (b) 6.8 mA, (c) 8.5 mA, and (d) 8.5 mA with parallel OF.

These results first, show the effect of polarization angle on the polarization stability of VCSEL's polarization modes at a fixed I_B and under orthogonal OF. Second, it shows the effect of polarization angle at a fixed I_B and under parallel OF. Under orthogonal OF with I_B of 6 mA the PS takes place at lower polarization angle of 6^0 and the VCSEL is lasing with the YP mode. While at I_B of 6.8 mA and 8.5 mA the PS is observed at 45^0. At the polarization angle of 45^0 the OF strength of the dominant mode (i.e., XP) is switched with that of the suppressed mode (i.e., YP) due to the polarization state effect. For parallel OF as shown in Fig. 9(d), there is no PS between the two polarization modes over the entire range of the polarization angle. This is because of the rotating polarization angle of the dominant mode, which does not enhance the suppressed mode. Note, a small change in the output power level of the XP mode at the polarization angle of 90^0, which is due to the lack of OF signal from the XP at this angle.

4. COMMENTS AND CONCLUSIONS

The influence of polarization angle and the OF levels on polarization stabilization of the VCSEL's polarization modes were experimentally investigated. Firstly, polarization stabilization was investigated under a fixed OF strength of -7dB with the rotating polarization angle. Secondly, polarization stabilization was identify when the VCSEL was subjected to different OF levels under fixed polarization angles of 0^0, 40^0 and 90^0 and in the absence of the polarization angle effect. For this purposes the L-I curve characteristics were monitored and the extinction ratio was measured for both the XP and YP modes. For the rotating polarization angles of 0^0 to 90^0 under a fixed OF level of – 7 dB, and orthogonal OF polarization instability was first observed at a polarization angle of >= 45^0. For a polarization angle of 0^0, where the parallel OF is applied, no PS was achieved over the entire range of the OF level. Both polarization angle and the OF level with different values of the bias current did induce polarization instability in the output power of the VCSEL. These results gave more insight in understanding the polarization modes behaviors of VCSEL under different conditions of orthogonal OF, the bias current and the rotating polarization angles, which are useful for polarization-sensitive applications.

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