Polarization switching and polarization mode hopping in quantum dot vertical-cavity surface-emitting lasers

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Abstract: We show experimentally that polarization mode hopping in quantum dot vertical cavity surface emitting lasers (VCSELs) takes place between nonorthogonal elliptically polarized modes. In contrast to quantum well VCSELs the average dwell time decreases with injection current. This decrease is by 8 orders of magnitude: from seconds to nanoseconds and is achieved without any modifications of the VCSEL internal anisotropies. The observed scaling happens in a range of currents as wide as 8 times the threshold value.

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References and links
1. Introduction

Many dynamical systems under the influence of noise show bistable hopping between two metastable states [1]. Classical picture of such a behavior is given by the Kramers escape over a potential barrier [2]. Since detail studies on polarization switching in quantum well (QW) vertical-cavity surface-emitting laser (VCSELs) show that it is often accompanied by a noise-driven polarization mode hopping (PMH) [3–5], these devices represent an ideal system for experimental study of such noise effects. Indeed, this issue has already been investigated for solitary devices [6–10] as well as for QW VCSELs subject to feedback [11–13] and optical injection [14]. The general conclusion is that the average dwell time between consecutive polarization hops depends on the potential barrier between the wells corresponding to distinct polarization states, and the strength of the spontaneous emission noise initiating the hopping. From an application point of view, polarization mode hopping is a source of polarization noise which introduces excess intensity noise and unwanted jitter thus degrades the system performance in terms of its bit-error-rate [15, 16].

Polarization mode hopping in QW VCSELs, if present, is only observed when the laser is biased in the vicinity of the current of an abrupt polarization switching. Since the polarization switching current changes from device to device, the average dwell time can be of the order of nanoseconds in devices showing polarization switching close to the lasing threshold but can also reach few seconds far from threshold, where the emission is dominated by the stimulated recombination. Consequently, the polarization switching current and the average dwell time can be regarded as still another parameters characterizing a particular device.

Current dependence of the average dwell time has been validated experimentally by external manipulation of the linear anisotropy [6,10] that determine the current at which the polarization switching between two orthogonal, linearly polarized states occurs. The results show that the average dwell time increases by 8 orders of magnitude when the polarization switching current is being shifted to larger values [6,10].

Much less is known for quantum dot (QD) VCSELs. In our last report [17] we have shown that these devices also exhibit polarization switching. Its characteristics, however, are in con-
trast to what is commonly observed in QW VCSELs. Here we show that the polarization mode hopping that accompanies the observed switching is also different: it takes place in an exceptionally wide range of currents and when the current is increased the average dwell time decreases by 8 orders of magnitude without any external manipulation of the inherent anisotropies. To our best knowledge, this is the first observation of such a diversified, in terms of dwell time scaling, dynamics of polarization mode hopping in a single VCSEL.

2. Results

The structure and composition of submonolayer (SML) QD VCSELs used in our experiment are described in detail in [18]. The emitted light is first collimated by an antireflection-coated aspherical lens with a focal length of 3.1 mm and then it is reflected by a mirror and passes through a polarizer to analyze its polarization properties. Finally, the light is coupled into a multimode fiber. To avoid feedback from its facet we use an optical isolator. The temperature of the wafer is actively stabilized up to a few milli Kelvin. Thermal variation of the laser wavelength is of 0.07 nm/K while the variation of the threshold current is of 0.009 mA/K. Out of 26 single-transverse mode devices, 7 exhibit very stable and reproducible polarization switching, which essentially are reflected in the polarization resolved power versus current characteristics shown in Fig. 1. The total output power is represented by black squares. Close to the lasing threshold the laser emits linearly polarized light along the $P_0$-direction ($LP_1$-mode, open circles; polarization angle is denoted as a subscript, e.g. $P_0$ means 0 deg with respect to the $y$ axis. When the current is increased, at a point $I_A$ the power measured at the $P_{90}$-direction (black triangles) starts growing. As shown later, point $I_A$ indicates the onset of stable, elliptically polarized emission ($EP_1$). When the current is further increased the polarization ellipse of the $EP_1$-mode rotates gradually, such that at point $I_S$ its major axis is aligned with $P_{-20}$-direction. Likewise, its ellipticity, calculated as the ratio of the power corresponding to the minor and major axes

![Fig. 1. Polarization resolved power-current characteristics of the investigated QD VCSEL. The inset shows schematically the orientation of elliptically polarized states after point $I_S$.](image-url)
of the polarization ellipse, increases gradually to 10%. At the point $I_s$ another elliptically polarized mode $EP_2$ appears and region of PMH between these two $EP$ modes starts. The major axis of $EP_2$ is aligned with $P_{20}$-direction, which shows that the modes $EP_1$ and $EP_2$ are non-orthogonal [17]. The amplitude of switching changes as a function of polarizer orientation and achieves maximum at $P_{05}$- and $P_{-45}$-directions. The power-current characteristics measured at these directions are represented in Fig. 1 by gray triangles and squares, respectively. The region of PMH extends to a point $I_R$.

In order to have a better insight into the features of the observed polarization mode hopping, as a next step we present optical spectra captured with scanning Fabry-Perot (FP) interferometer. The spectra shown in Fig. 2 are captured just after the point $I_s$, where PMH is slower than

![Fig. 2. Polarization resolved optical spectra at $I = 1.85$ mA for different orientations of the polarizer (P). The inset in panel (a) shows RF spectrum captured at $P_{05}$. Polarization angle is denoted as a subscript, e.g. $P_{20}$ means 20 deg with respect to the y axis.](image)

do the maximum bandwidth of the FP interferometer (50 Hz). The respective panels correspond to different orientations of the polarizer. All spectra show a strong peak at frequency of 27 GHz and low-amplitude equidistant sidebands. As can be seen from Fig. 2, at the orientations of the polarizer denoted in the figure, the main spectral peak switches between two levels, which correspond to linear projections of the $EP_1$ and $EP_2$ modes. Such switching clearly shows that the main peak possesses an internal structure however, the resolution of 2 GHz of our FP interferometer is not sufficient to resolve the two modes spectrally. Nevertheless, the laser biased just after the point $I_s$ stays in a given $EP$ mode for a few seconds and, therefore, it is possible to find, with sufficient precision, the orientations of the polarizer at which the individual spectral components achieve their maxima. In the case shown in Fig. 2a, the peak represented by the black curve achieves maximum at $P_{20}$ and, therefore, it corresponds to the mode which we have marked as $EP_2$. At a certain moment the laser emission switches to the $EP_1$-mode so that the amplitude of the main peak drops to a value corresponding to a linear projection of $EP_1$ mode on $P_{20}$, see the gray curve in Fig. 2a. Likewise, as shown in Fig. 2c, the $EP_1$-mode achieves its
maximum at $P_{-20}$ (gray curve). The black curve in this figure corresponds, therefore, to linear projection of $EP_2$ on $P_{-20}$. The so determined orientations of the major axes of the $EP_1$ and $EP_2$ modes prove their nonorthogonality. Figure 2b shows FP spectra captured at orientation of the polarizer corresponding to the minor axis of $EP_2$, i.e. $P_{110}$, black curve. The gray curve in this figure represents a linear projection of $EP_1$ on $P_{110}$. Likewise, Fig. 2d shows FP spectra at $P_{70}$, which correspond to minor axis of the $EP_1$ mode, gray curve, and a linear projection of $EP_2$ mode, black curve, respectively. Both Fig. 2b and Fig. 2d prove, that the $EP$ modes involved in polarization mode hopping, indeed, possess residual ellipticity.

As already mentioned, the main spectral component in Fig. 2 possesses low-amplitude, equidistant sidebands. They appear near the $I_\text{s}$ point, which is manifested by a strong peak at 8 GHz in the radio frequency spectrum (RF), see the inset in Fig. 2a. Note, that similar observations have been reported for polarization switching involving dynamical states in QW VCSELs [19], i.e. the increase of the ellipticity angle close to the switching point has been accompanied by the appearance of sidebands in the optical spectrum. Their frequency has been attributed to an effective birefringence expressed as the sum of the linear birefringence observed at the lasing threshold and the non-linear contributions due to saturable dispersion and spin dynamics [19]. In our SML QD VCSELs, however, the sidebands in the optical spectra in PMH regime have different origin as shown hereafter.

In Fig. 3 we show the relaxation oscillation frequency ($f_{RO}$) as a function of the square root of the pump current above threshold. A linear interpolation of the experimental data with:

$$f_{RO} = A(I - I_{TH})^{1/2}$$

$$A = 5.71 \pm 0.03 \text{ [GHz/mA}^{1/2}\text{]}$$

gives a proportionality constant $A$ of $5.71 \pm 0.03$ GHz/mA$^{0.5}$. We then use Eq. (1) to extrapolate the value of the relaxation oscillation frequency at the current of 1.85 mA. The value
of 7.31 GHz is close to the frequency of 8 GHz of the RF peak in Fig. 2a and, therefore, we attribute the spectral sidebands to a low-amplitude time dependent modulation of the laser response at the frequency of the relaxation oscillations excited by polarization instabilities.

As already mentioned, the region of PMH starts at the point \( I_S \) and extends over a wide range of currents up to \( I_R \). This is in sharp contrast to PMH in QW VCSELs, which occurs only when the laser is biased close to the abrupt polarization switching [10]. Another distinctive feature is its dynamics. Examples of time traces captured at the polarizer orientation of \( P_{45} \) and different currents are shown in Fig. 4. Just after \( I_S \), at \( I = 1.81 \) mA, polarization mode hopping is asymmetric, i.e. the laser stays most of the time in one \( EP \) mode and exhibits rapid switches to the other mode every few seconds, see Fig. 4a. At around \( I = 2.0 \) mA PMH becomes symmetric, while the average dwell time decreases to microseconds, see Fig. 4b. At still larger currents the average dwell time decreases to nanoseconds (see Fig. 4c,d,e), although there is also a subtle increase at around \( I = 3.2 \) mA (see Fig. 4d).

Current dependence of the dynamics of the observed PMH is summarized in Fig. 5. Contrary to the scaling of the dwell time in QW VCSELs, the average dwell time in QD VCSELs decreases with injection current. This decrease is by 8 orders of magnitude: from seconds to nanoseconds and is achieved without any modifications of the internal anisotropies. The observed scaling happens in polarization mode hopping range of currents as wide as 8 times the threshold current.

After the point \( I_R \) polarization mode hopping disappears, but, unlike in the polarization switching involving dynamical states in QW VCSELs, the laser does not switch to the \( LP_2 \) mode, i.e. polarization mode that is suppressed close to threshold. Instead, it exhibits two-mode emission with dominant \( LP_1 \), which also dominates before the onset of elliptically polarized emission, and weaker \( LP_2 \), see Fig. 6. Moreover, each \( LP \) mode is accompanied by a single low-amplitude peak of the same polarization. The RF spectrum shown in the inset of Fig. 6 includes two strong beating signals. One of them, at 4.8 GHz, corresponds to the frequency splitting between the two dominating \( LP \) modes that in the FP spectrum are split by 5.58 GHz. The difference between the RF beat and the mode interval in FP spectra results from the limited resolution of the FP interferometer. The frequency of 4.8 GHz can be regarded as corresponding to the birefringence splitting between the two polarization modes. The remaining spectral component appears at 9.8 GHz and corresponds to the frequency splitting between \( LP \) mode and a small-amplitude peak of the same polarization, which again we interpret as slightly excited relaxation oscillations at this current (the relaxation oscillation frequency at 4.45 mA estimated from Eq. (1) amounts to 11.75 GHz).

3. Conclusion

In this paper we show experimental characterization of optical spectra and dynamics of polarization mode hopping in QD VCSELs. In contrast to what is observed in QW VCSELs, polarization mode hopping takes place between nonorthogonal elliptically polarized modes with frequency splitting smaller than 2 GHz and is observed in an exceptionally wide range of currents. Similarly to polarization switching involving dynamical states in QW VCSEL, the increase of the ellipticity of the lasing polarization component close to the point at which polarization switching starts is accompanied by the appearance of sidebands in the optical spectrum. We attribute these sidebands to a low-amplitude time dependent modulation of the laser response at the frequency of the relaxation oscillations excited by polarization instabilities.

Another striking difference between the observed scenario and polarization switching in QW VCSELs involving dynamical states is that instead of switching to the \( LP \) mode that is suppressed close to threshold, after the region of polarization mode hopping the laser exhibits two-mode emission with dominant \( LP \) mode that lases also before the onset of elliptically polarized
Fig. 4. Time traces at the current of a) 1.81 mA, b) 2.0 mA, c) 2.6 mA, d) 3.2 mA, e) 3.6 mA at the polarizer direction corresponding to the maximum amplitude of switching, i.e. $P_{45}$. 
Fig. 5. Experimental data for the current dependence of the average dwell time for both \( EP \) modes calculated from the time traces captured at the polarizer orientation of \( P_{45} \).

Fig. 6. Polarization resolved optical spectra at \( I = 4.45 \) mA. The inset shows RF spectrum captured at \( P_{45} \).
emission, and a weaker orthogonal one. The frequency splitting between these two modes can be regarded as a measure of birefringence and is of 4.8 GHz. Each LP mode is accompanied by a single low-amplitude peak of the same polarization split in frequency by 9.8 GHz, which we again interpret as excitation of relaxation oscillations at this current.

Another distinctive feature of the observed polarization mode hopping is its dynamics. The average dwell time decreases when the current is increased. This decrease is by 8 orders of magnitude: from seconds to nanoseconds. Interestingly, such behavior is observed without any external manipulation of the VCSEL anisotropies. To our best knowledge, this is the first observation of such a diversified, in terms of time scaling, dynamics of polarization mode hopping in a single VCSEL.

We would like to stress that the reported polarization instabilities are important for applications of QD-VCSELs in optical telecom and datacom systems. Indeed, it has been shown that polarization mode hopping in QW VCSELs is a source of polarization noise which introduces excess intensity noise and unwanted jitters [15, 16]. Ultimately, these effects will degrade the system performance in terms of its bit-error-rate [15].

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