Fast, electrically controlled polarization modulation of multimode vertical-cavity surface-emitting lasers by RF frequency modulation

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Abstract: We report on a study of polarization properties of asymmetric, multimode vertical-cavity surface-emitting lasers (VCSEL) subjected to electrical RF modulation. When subjected to RF modulation, complex frequency-dependent polarization properties, especially near the polarization switching point are revealed. We propose a scheme of rapidly switching the two RF frequencies modulating the VCSEL, in order to achieve fast polarization modulation in these VCSEL. Polarization modulation up to 300 MHz by modulating the RF frequency and up to 1.5 GHz with RF power modulation has been demonstrated; the fastest reported electrically controlled polarization modulation for multimode VCSELs.

OCIS codes: (140.0140) Lasers and laser optics; (250.0250) Optoelectronics.

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1. Introduction

Polarization properties of VCSELs are extremely interesting and yet, poorly understood. It is well known [1] that VCSELs generally exhibit abrupt polarization switching as a function of bias current, from higher to lower frequency mode (type-I switching) or vice-versa (type-II switching), depending on the detuning between the polarization modes and their relative position with respect to the gain spectrum [2]. It has also been found that the VCSEL polarization can be affected by the temperature [2], magnitude and directionality of current injection [3–6], stress [7] and with polarized optical injection. Theoretical modeling based on 'Spin-Flip Model' [8,9] has been successfully used to predict certain static [10, 11] and dynamic [12–14] polarization properties of VCSELs. However, the exact nature the complex dynamics accompanied by the polarization switching, especially in multimode VCSELs in presence of current modulation at GHz frequency scale are largely unknown. In this paper we report on experimental observations of extremely rich polarization resolved frequency response of current modulated asymmetric multimode VCSELs, showing that, even though at low frequencies VCSEL exhibits only one type of polarization, it still exhibits polarization mode competition at higher frequencies. Furthermore, we can use this frequency dependence to modulate the polarization output of the VCSEL, at GHz rate, by simply varying the RF frequency or power. High resolution optical spectral measurements reveal the details on the polarization mode-competition for multi-transverse mode, asymmetric VCSEL.

Although the polarization modulation up to 50 MHz has been previously demonstrated [15,16], the thermal nature of this effects limits high speed operation [17]. High-speed polarization modulation has been demonstrated with optical injection [18,19], but it requires complex optical injection locking and polarization controllable master laser source, thus, is not scalable. Polarization self-modulation at much higher frequencies has also been reported [20,21]. We have previously demonstrated high-speed polarization modulation by modulating the electrical RF power applied to a single mode VCSEL [22,23]. In this paper, we report on a new scheme for polarization modulation by rapidly switching the frequency of RF signal

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incident on the VCSEL. This scheme leads to polarization modulation with higher modulation depths. Furthermore, since the polarization modulation is achieved by varying only the frequency of electrical signal, the results prove that the polarization modulation is purely due to electrical frequency variation, and not caused by thermal effects. We also note that faster polarization modulation, up to 1.5 GHz has also been obtained, even in multimode regime, by modulating the RF power. This ultrafast polarization modulation does not require any special fabrication steps, or a complex experimental setup, as it can be performed on simple two terminal VCSELs.

2. Design and fabrication

VCSELs used for these measurements consisted of highly-strained InGaAs/GaAs quantum-well (QW) active region, operating at 1060 nm. Details of this design can be found in Zheng et al [24]. The material was processed into elliptical mesa VCSELs with varying sizes. The electrical and optical confinement was provided with a tapered oxide aperture, with a total oxidation length of 7 μm. The devices have a simple two contact geometry with a bottom-emitting configuration. The backside of the substrate was coated with an antireflection (AR) coating of magnesium oxide (MgO) after fabrication, to avoid the optical feedback during measurements.

3. Experimental results

After fabrication, polarization resolved light-current (L-I) characteristics were measured using a Si-based broad-area DC detector and a wire-grid polarizer. A constant stage temperature of 20°C was maintained in all the measurements. Y direction is the direction which is along the major axis of ellipse, which is orthogonal to X. X and Y are found to be aligned to <110> and$<1\bar{1}0>$ crystalline directions. L-I characteristic measured from one of the elliptical VCSELs is shown in Fig. 1(a). In this VCSEL, major axis is 22μm and minor axis is 16μm. It should be noted that the ellipticity of the actual oxide aperture is different than the outer mesa geometry. It is clear that this highly asymmetric VCSEL still supports both X and Y linearly polarized modes. Interesting thing to note here is that although the VCSEL operates in multimode regime above current of 2.8 mA, it still exhibits very high extinction ratio thermal polarization switching. This behavior, observed in several asymmetric VCSELs, is in contrast with the traditional circular mesa devices. Polarization resolved optical spectral measurements have been plotted as a function of bias current in Figs. 1(b) and 1(c). These measurements reveal that the high contrast switching even at higher bias currents in multimode regime is due to the two polarization modes corresponding to the fundamental transverse mode, switch back and forth as a function of bias current. Due to the asymmetric nature of the VCSEL, the threshold for first higher-order transverse mode in one direction is much lower than the orthogonal mode. As a result, only the fundamental mode emits in one of the two orthogonal polarizations, even in the multimode regime, resulting in high contrast polarization switching. The multiple polarization switching in the fundamental mode is believed to be a result of imperfect AR coating, resulting in weak optical feedback [25].

When the VCSELs are subjected to electrical RF modulation with 2 dBm nominal power, at RF frequencies ranging from 0.1 GHz to 20 GHz, a complex nature of polarization dynamics is revealed. Figures 2 (a) and 2(b) shows the contour plots of modulation response (S_{21}) measured from this VCSEL at different bias currents for X polarization, Y polarization, respectively. The ratio of powers in X and Y mode is shown in Fig. 2(c), in which red corresponds to X mode and blue corresponds to Y mode. It is apparent that even though at DC, the VCSEL exhibits one of the two polarizations, there is a rich, complimentary, frequency dependence of powers in each linear polarization mode, especially near the polarization switching point. It is to be noted that this dependence has similar functional form for both, type I (from high frequency mode to low frequency mode) and type II polarization switch (from low frequency mode to high frequency mode). Figure 2(d) shows the individual

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response at bias current of 4.4 mA, corresponding to the multimode regime, showing that the polarization contrast ratio in excess of 30 dB can be obtained by this technique. These measurements are extremely repeatable, proving that the frequencies of polarization switch are not determined by spontaneous emission noise. Similar behavior of rapidly switching polarization direction was also observed in single mode regime. In both the regimes, there is strong frequency dependence to the modulation amplitude, with sharp peaks in one type of polarization corresponding to dips in other polarization. Due to relatively small modulation depth and high bias current operation, period doubling nonlinear dynamics were not observed.

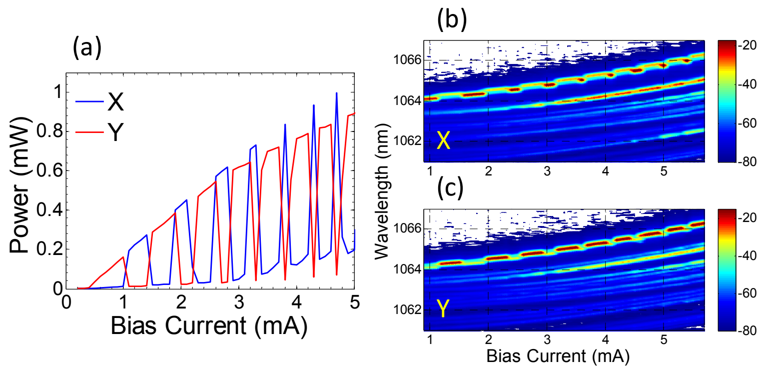

Fig. 1. (a) Measured L-I characteristics of an elliptical, oxide confined VCSEL showing high polarization contrast ratio even in multimode regime (b)-(c) high resolution optical spectral measurements as a function of current, for X and Y polarization.

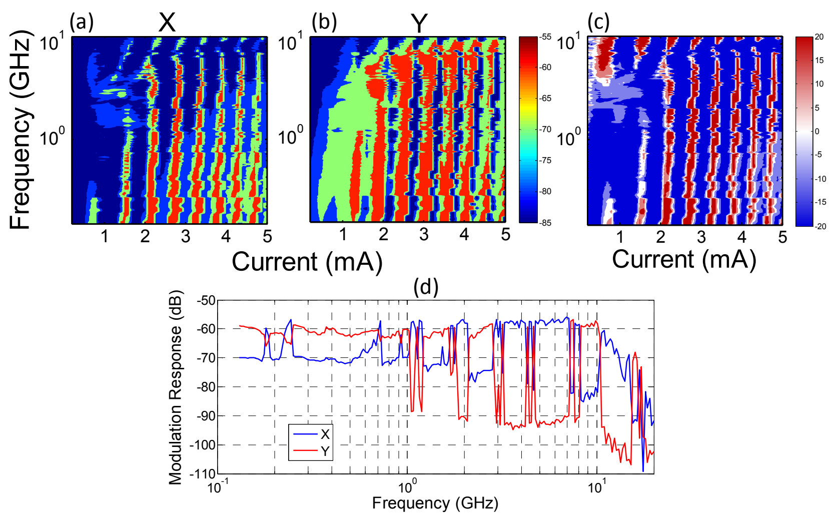

Fig. 2. Contour plots of modulation responses at different bias currents, for (a) X-polarization, (b) Y-polarization and (c) Difference between X and Y, showing the mode stability plot for the VCSEL (d) Modulation response 4.4mA, showing abrupt switching between X and Y modes as a function of frequency.

Using this strong frequency dependence, it is possible to modulate the polarization state of the VCSEL. For this, it is necessary to switch the frequency of the current modulation of the VCSEL at a rapid rate. This was achieved with a setup schematically shown in Fig. 3. Two RF source of equal amplitude are passed through double-balanced mixers, with direct and inverted signal from a square-wave generator, respectively. At the output of each mixer, the corresponding RF signal is switched on and off, exactly out-of-phase with each other. The output was then combined in a resistive splitter, which produces a RF signal of constant

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amplitude and with frequency varying at the same rate as the square wave frequency (f_m), as shown in the inset of Fig. 3. Path lengths of the two arms were matched in order to get a minimum overlap between the two RF signal bursts. This RF signal was then amplified to the same power levels used in the previous measurement (2 dBm nominal power) and applied to the VCSEL along with a fixed DC bias using a bias-tee network. The output of the VCSEL was collimated onto a multimode fiber, after passing through a wire-grid polarizer, and then detected by a high speed detector. The output of the detector was amplified and then passed through a low-pass filter, which blocks the RF carrier frequencies (f_1 and f_2), while transmitting f_m for an envelope detection. This measurement setup ensures that all the parameters except the frequency of RF signal are unchanged, and the observed polarization modulation can only be explained by the RF frequency induced polarization modulation effect described earlier.

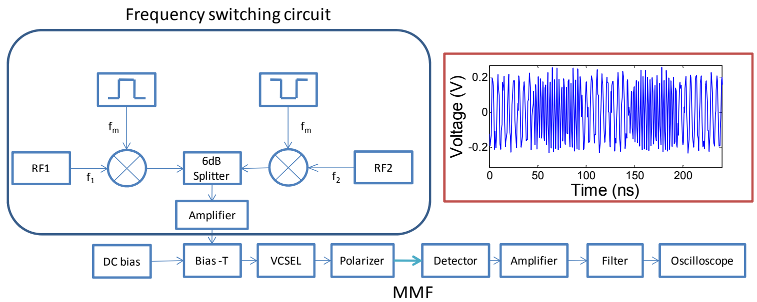

Fig. 3. Schematics of the experimental setup used for rapidly switching between f_1 and f_2 for modulating the VCSEL. The inset shows the output of the amplifier before the bias-T network.

Figures 4 (a)-(c) shows the modulation response for the VCSEL in multimode regime, at three different f_m. For this measurement, f_1 and f_2 was set to 5.4 GHz and 2.25 GHz, respectively. It is clear that, up to 300 MHz modulation frequency, the two polarizations are 180° out-of-phase with each other, indicating that the frequency sweep is changing the power in each linear polarization mode, as expected. At higher frequencies, the two polarization modes do not change exactly 180° from each other. Here, it should be noted that f_m of 300 MHz means that each polarization mode is being modulated at 300 MHz frequency; the actual polarization change is occurring at twice the frequency. This polarization modulation frequency is much higher than the typical polarization switching frequencies due to thermal polarization switching or mode hopping. It should also be noted that the DC component of the electrical signal has been blocked by the amplifier. Corresponding DC measurements reveal that polarization contrast ratio of above 15:1 can be obtained by this technique.

It is possible to further increase the polarization modulation speed by modulating the RF power instead of RF frequency, as previously shown [22,23] for single mode VCSELs. For this, only one RF source is needed, the output of which is combined with a square wave, similar to that shown in Fig. 3. In this case, the polarization modulation takes place due to the RF power dependence of polarization for the VCSEL subjected to a constant RF frequency (not shown here). Figure 5 shows the polarization modulation response obtained with this technique, in multimode regime of the VCSEL, at the modulation frequency of 1.5 GHz. A sinusoidal pattern was obtained due to the low pass filter used to block the carrier RF. VCSEL was biased at 4.4 mA, and RF frequency of 4.95 GHz was used for this experiment. It is to be noted that in this case, the polarization modulation is faster than the frequency-sweep experiment described earlier, because only the faster frequency is used as the carrier frequency. This polarization modulation frequency is, by far, the fastest reported for polarization modulation in electrically-controlled multimode VCSELs.

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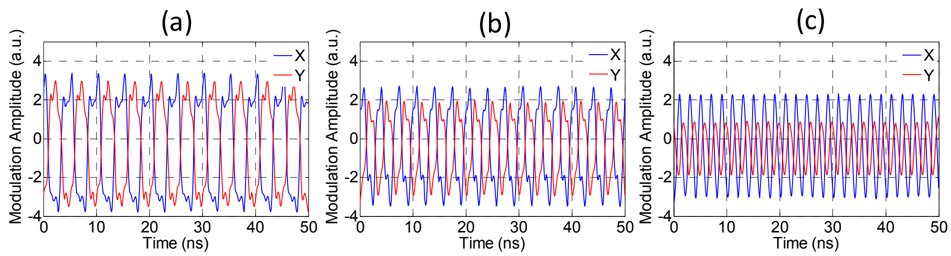

Fig. 4. Polarization modulation of the VCSEL, subjected to varying RF signal with frequency modulated at (a) 200 MHz (b) 300 MHz and (c) 500 MHz.

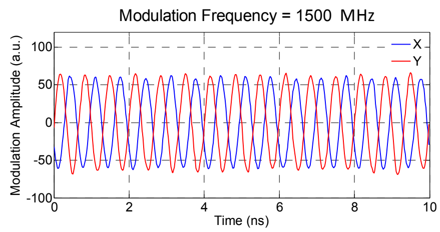

Fig. 5. Polarization modulation response for the VCSEL subjected to a fixed RF frequency and the RF power modulated at 1.5 GHz.

4. Conclusions

In conclusion, we report on the observations of rich and complex frequency response of a VCSEL subjected to RF current modulation. It has been observed that near the polarization switching point, VCSEL can be controllably switched between the two linear polarization modes as a function of the frequency of current modulation. We demonstrate that, using this effect, it is possible to modulate the polarization of the VCSEL at high speeds, either by modulating the frequency of RF signal, or the power of RF signal applied to the VCSEL. Polarization modulation of 300 MHz and 1.5 GHz has been demonstrated with these two techniques, respectively, in the multimode regime of the VCSEL.

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