Parametric investigation of polarization properties of VCSELs subject to optical feedback from an extremely-short external-cavity

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We use a rate equation model for VCSELs subject to optical feedback from an extremely short external cavity (ESEC) and investigate the parametric dependence of their polarization properties. We show strong periodic dependence of the polarization switching (PS) currents on the ESEC length that becomes strongly asymmetric when increasing the external mirror reflectivity. This asymmetry provides the possibility to prevent PS for any injection current, constituting a new way of polarization stabilization in VCSELs.

Introduction

Vertical-cavity surface-emitting lasers (VCSEL) are a new generation of semiconductor lasers that possesses many advantages over the edge emitting lasers (EEL) like circular beam shape, low threshold currents and the possibility to be maid in two dimensional arrays. However, VCSELs have the drawback of non stable polarization properties [1, 2]. Different mechanisms have been proposed to achieve polarization control and stabilization like nonsymmetric shape [3], diffractive grating [4] and anisotropic strain [2]. In this paper we investigate the effect of optical feedback (OF) from an extremely-short external-cavity (ESEC) on the polarization properties of VCSELs, demonstrating a new way to achieve polarization stabilization.

Often the semiconductor laser steady-state and dynamical characteristics, are described by time-delayed rate equations that take into account a single roundtrip in the external cavity (EC) (the well known Lang Kobayashi model [5]) or multiple roundtrips. For the case of ESEC the time-delay in the EC is very small (of the order of $0.01ps$) and the feedback optical field can be considered as instantaneous [6, 7, 8]. Therefore we can simulate our real system (see fig.1(a)) as a simple VCSEL that has the same characteristics as the real one except for the top mirror reflection coefficient (r_2), which is replaced by an effective reflection coefficient r_{eff} that includes all the effects of the optical feedback (see fig.1(b)). The effective amplitude reflection coefficients are constructed as summations of the initial reflection of the top mirror of the VCSEL (r_2) and all the reflections from the external mirror after 1,2,3,4,... round trips in the external cavity [9]. Furthermore, we consider the VCSEL working in a single transverse mode regime, i.e. we use the complex slowly varying fields for the two linearly polarized (LP) states, and the effect of the feedback is taken into account in the phenomenological rate equations trough the photon lifetimes of the two LP modes, which depend on the module of the effective reflection coefficients [9].

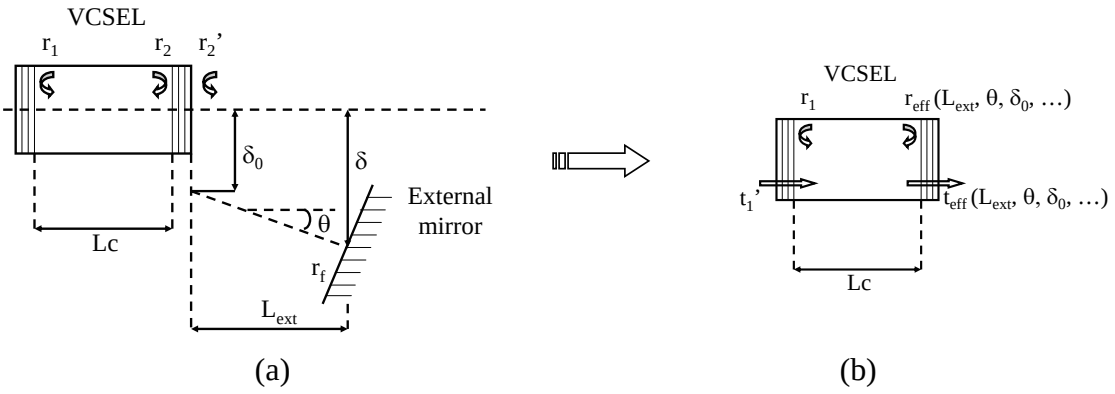

Figure 1: *a) Schematic representation of the system formed by a VCSEL and an external mirror placed in front of it at a distance L_{ext}. The external mirror is placed at an angle* θ *and with a transverse offset* δ *respect to the normal to the VCSEL surface. r_2 and r_1 are the amplitude reflection coefficients of the top and the bottom mirror of the VCSEL, and r_f is the reflection coefficient of the external mirror. b) Model of VCSEL in ESEC optical feedback configuration, where r_{eff} includes all the effects of the optical feedback.*

Numerical results

Taking typical parameters for a VCSEL, as $\tau_e = 1ns$, $g_{H(L)} = 8(8.013)\ 10^{-8}\ \mu m^2$, $dg_{H(L)}/dJ = -1(-2)\ 10^{-10}\ \mu m^2\ mA^{-1}$ and $\varepsilon_{s(c)} = 2.5(5)\ 10^{-7}\ \mu m^3$ we numerically make a sweep of the injected current for a fixed EC length and a sweep of the external cavity length for a fixed current. The polarization resolved optical power emitted by the VCSEL in both cases is represented in fig.2. The VCSEL switches from one LP mode to the orthogonal one by increasing the injected current and by decreasing it, describing a bistable region. Comparing figs.2(a) and 2(b) it can be appreciated that the currents at which the switches take place and the widths of the bistable regions dramatically change by changing the EC length. The noticeable superlinear dependence of the power with the current observed in fig.2(a) is due to the feedback (at an EC length of $18.9\mu m$ the photon lifetime increases by increasing the wavelength of operation of the device).
On the other hand, if we fix the injection current and make a sweep of the EC length, we observe a modulation of the total power emitted by the VCSEL with a period of half of the wavelength of operation of the device (see figs.2(c) and (d)). During this modulation a periodic switch from one LP mode to the other occurs as a consecuence of a change of the sign of the net gain difference between the LP modes induced by the frequency splitting between the VCSEL LP modes [9]. In one period of modulation two consecutive PS are observed. The positions at which the two PS appear in each period are different if we increase or decrease the EC length, enclosing a hysteresis region. By biasing the VCSEL at two different currents (see figs.2(c) and 2(d)) one can appreciate that the position at which the switches take place and the hysteresis widths of those switches strongly depend on the injected current.
Fig.2 can be summarize in a map of the PS currents and the hysteresis region versus the injected current and the EC length (see fig.3). In this way figs.2(a),(b),(c) and (d) correspond respectively to cuts A, B, C and D in fig.3(b). As can be observed from fig.3 the PS currents are modulated with a period of half of the wavelength of operation of the VCSEL due to the periodic change of the phase of the effective reflection coefficient [10].

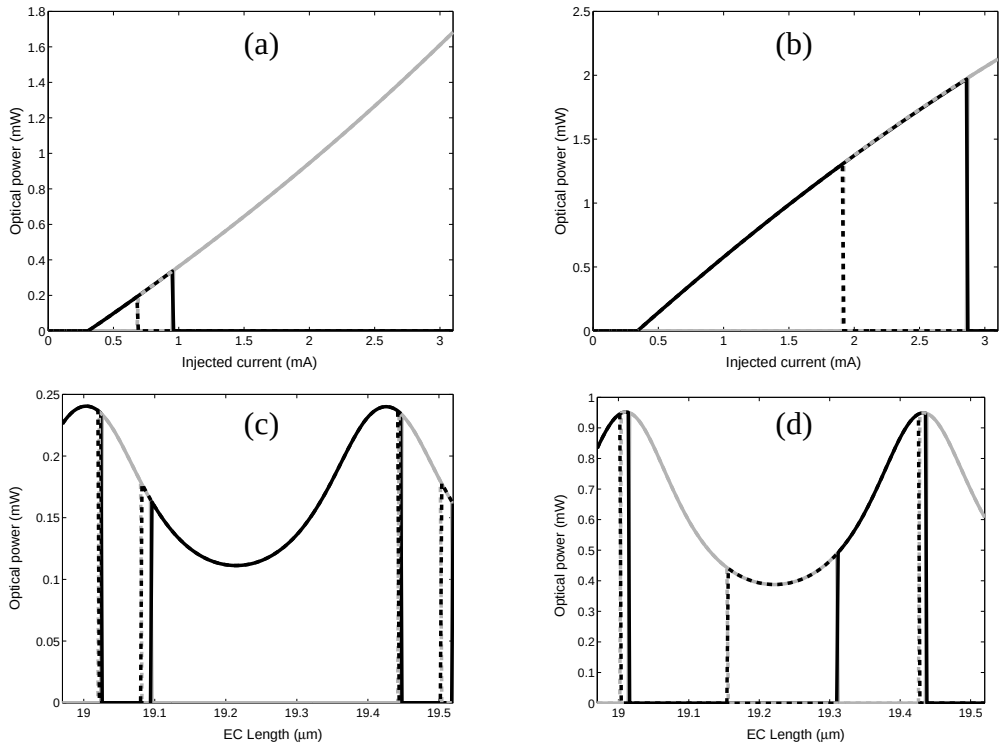

Figure 2: *Polarization resolved output power as a function of the injected current and the EC length for a VCSEL with OF from an ESEC. The EC length is fixed to (a) 19.11μm and (b) 19.4μm, and the injected current is fixed to (c) J=0.6mA and (d) J=1.35mA. The black (grey) line represents the low (high) frequency LP mode, while solid (dashed) lines represent the two LP modes for increasing (decreasing) the EC length or the injected current.*

Fig.3 indicates that one is able to select the width of the bistable region and the position of the PS currents in a huge range by changing the EC length within a subwavelength range. The higher the reflectivity of the external mirror is the bigger is the amplitude of modulation of the PS currents (see fig.3), leading to a disappearance of the PS for a certain range of EC length within a period of modulation (see fig.3(c)). Therefore, the polarization of the emitted light will not depend on the injected current at that range of EC lengths, constituting a new way to achieve polarization stabilization in VCSELs.
However, the smaller the frequency splitting is, the smaller would be the amplitude of modulation that can prevent achieving polarization stabilization. Fig.3(d) shows the minimum external reflection coefficient necessary to achieve polarization stabilization in a practical VCSEL subject to optical feedback from an ESEC, versus the frequency splitting between the two LP modes, for three different EC lengths. As it could be expected, the larger the frequency splitting is the lower external reflection coefficient is needed in order to achieve polarization stabilization by selecting the EC length. Moreover, fig.3(d) shows that by choosing the proper EC length and a high external reflection coefficient, polarization stabilization is possible if the frequency splitting between the VCSEL LP modes is bigger than 0.4GHz, i.e. practically always.
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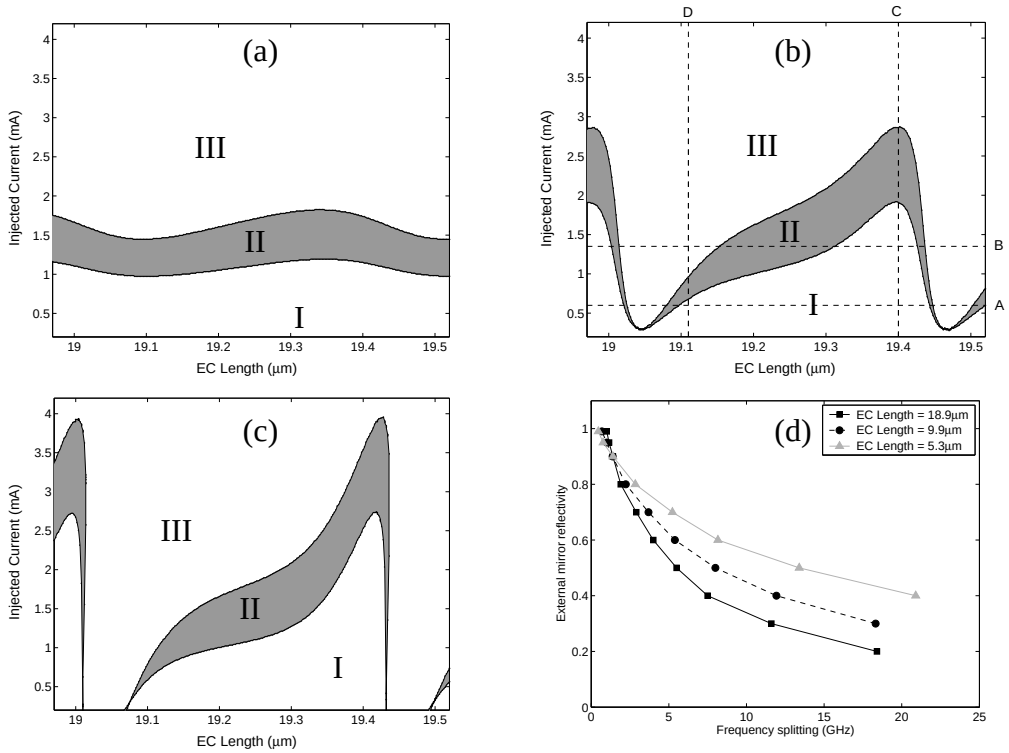

Figure 3: *Mapping of bistability of a VCSEL affected by feedback from an ESEC. Three different zones are observed. In zone I(III) the VCSEL is stable and emits in its low(high) frequency mode. The zone II represented in grey is placed in between zone I and III and correspond to the region at which the VCSEL is bistable. Here* $\varepsilon_{s(c)} = 2.5(5)\ 10^{-7}\ \mu m^3$, $r_2 = 0.9972$ *and the reflectivity of the external mirror (*r_f*) is set to: (a) 0.1 (b) 0.5 and (c) 0.7. (d) Minimum external reflection coefficient necessary to achieve polarization stabilization in a practical VCSEL subject to optical feedback from an ESEC, versus the frequency splitting between the LP modes, for three different EC lengths.*

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