Experimental studies of pulse packages in short external cavity VCSELs

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We investigate experimentally the influence of delayed optical feedback from a short external cavity on the emission dynamics of vertical-cavity surface-emitting semiconductor lasers (VCSELs). We unveil the presence of pulse packages (PP) in the total intensity of the emitted light. The investigations of the polarization resolved temporal dynamics show that for currents corresponding to a stable polarization emission of the solitary VCSELs the PP dynamics usually occur in the dominant polarization mode only, defining type I PP dynamics. However, in some cases the PP dynamics persists in both polarizations simultaneously, indicating second (type II) type of PP dynamics.

Introduction

In Vertical-Cavity Surface-Emitting Lasers (VCSELs) the short resonant cavity length allows for one longitudinal mode emission only. In spite of the several advantages of VCSELs over standard Edge Emitting semiconductor Lasers (EELs), the circular geometry and the structure of a resonant cavity in VCSELs does not fix the polarization of the emitted light. VCSELs either emit light in one of the two orthogonally (x and y) linearly polarized (LP) directions or switch from one to another LP mode as the injection current is changed [1]. It has also been shown that VCSELs are similarly sensitive to external optical feedback (OF) as EELs [2]. Feedback in semiconductor lasers (SL) is a very important subject from an application point of view, because it can easily destroy the stable laser operation and induce complex dynamics [3]. The appearance of different dynamical regimes is basically determined by the injection current [4] and the main feedback parameters [5]; the strength of the feedback; i.e. the amount of light that enters back the active region of the SL, the length of the external cavity (EC) and the feedback phase. In the case of long EC and moderate feedback chaotic regimes arise such as low-frequency fluctuations (LFF), characterized by a sudden, random dropouts which are followed by stepwise recovery. In the case of short EC regular pulse packages (PP) regime has been recently found in EELs [6, 7] which corresponds to emission of pulses at the delay time modulated by the slower time-periodic envelope. The existence of the two LP modes in VCSELs can give rise to additional interesting polarization dynamics due to feedback, like feedback induced polarization switching [8].

In this paper, we experimentally study the influence of OF on the emission dynamics of VCSELs in the short EC regime. We demonstrate the existence of a PP regime which significantly differs from the PP regime observed in EELs. The existence of two LP modes in VCSELs induces additional degree of freedom in the system that makes the PP dynamics more complicated. The polarization resolved temporal dynamics show that for pump currents corresponding to a stable polarization emission of the solitary VCSELs, the PP dynamics might occur in the dominant polarization mode only, defining type I PP dynamics. However, in most cases the PP dynamics persists in both polarizations simultaneously, indicating type II PP dynamics.

Experimental Setup

The scheme of our experimental setup is shown in Fig. 1. We use a temperature-stabilized air-post GaInAs VCSEL emitting at $\lambda = 968$nm. In the solitary laser case the threshold current of the VCSEL is 3.7mA and the VCSEL switches from x to y polarization mode at 4.2mA. The output beam is collimated by an antireflection-coated aspheric lens (C), and partially reflected from an external mirror with reflectivity of 30%. To align the feedback, the standard technic of a maximum threshold reduction (of about 22%) is used. The polarizing beam splitter (PBS) directs the two fundamental polarization modes into the two perpendicular arms of the detection. The optical isolators (ISO) are used to

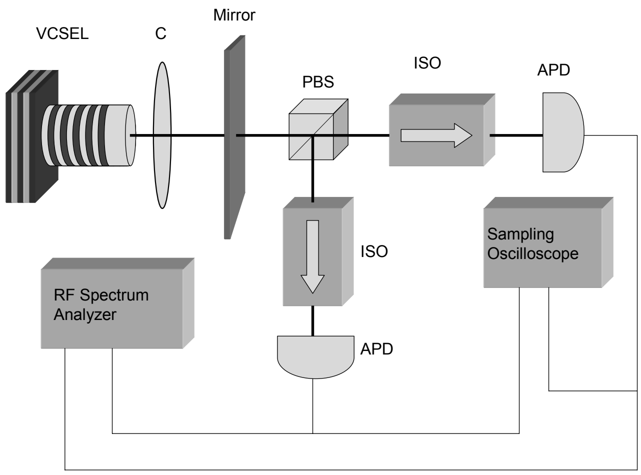

Figure 1: Schematic illustration of the experimental setup: C is the collimating lens, PBS, polarizing beam splitter, ISO, optical isolators, APD, avalanche photodiodes.

prevent any unwanted feedback from the detection branches. We detect the light by means of the two ultrafast photo detectors (APD) (New Focus NFI-1554-A-50) with 12GHz bandwidth and wavelength range $400 - 1650$nm. The electronic signal is analyzed with a digital oscilloscope (Tektronix SCD500) and an electrical spectrum analyzer (Tektronix 2755AP). In order to observe the dynamics in the two polarizations simultaneously, the two detecting branches have been taken with equal length.

Experimental Results

In fig. 2(a) we show a typical time trace of the total intensity of the VCSEL subject to external optical feedback in the short EC regime. The VCSEL injection current is 3.2mA and the EC length is around 6.6cm. Figure 2(a) shows a periodic train of pulses separated by intervals of low intensity. In each package the VCSEL emits pulses of high intensity at regularly spaced time intervals corresponding to the EC round trip time. This dynamical behavior is very similar to the one observed by Heil *et.al.* in [6] for the case of EELs. In fig. 2(b) we plot the corresponding autocorrelation function of the temporal dynamics in PP regime. In the autocorrelation function we find regularly separated peaks corresponding to the period of the envelope of the PP. We see that the regularity is kept for long time intervals (more than several hundreds of ns; i.e. several tens of pulse packages) revealing the characteristic feature of this dynamics. As shown in the inset of fig. 2(b),

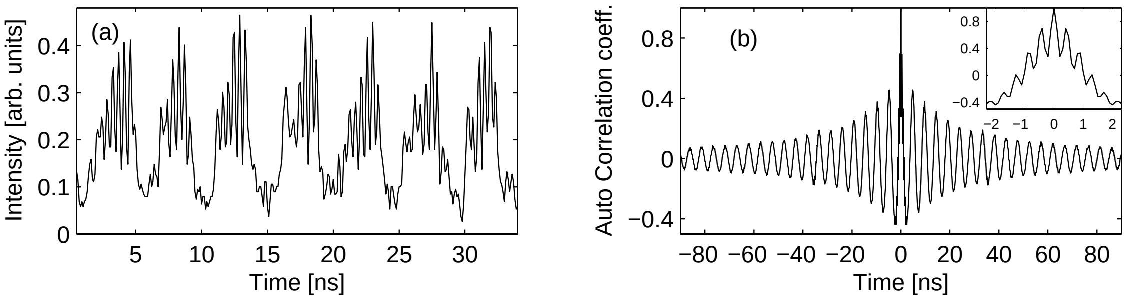

Figure 2: In (a) a typical time trace of a laser intensity in pulse packages regime and in (b) its auto-correlation function. The inset of plot (b) illustrates the regularity of the PP dynamics at the multiples of the delay.

the autocorrelation function also indicates the presence of the pulses at the delay time (at around 0.4ns). We point out that the modulation depth of the pulses with the period of the delay time is relatively small due to the limited analog bandwidth of the scope.

Polarization resolved dynamics in PP regime for the same set of conditions as in fig. 2 is presented in fig. 3. The upper (lower) set of graphs corresponds to the x (y) polarization mode of the VCSEL. The presence of the PP dynamics can be clearly recognized in both LP modes. However, the amplitude of the pulses in x-LP mode seem to be more pronounced than in the orthogonal y-LP mode.

As can be seen from fig. 3, the PP dynamics in the individual polarization modes is much less regular than the dynamics observed in the total intensity. In the polarization resolved dynamics, we observe on top of the PP dynamics the consequences of mode competition which leads to decrease of the regularity of the PP dynamics. We point out, that the PP in the two modes are synchronized on the time scale of the PP, i.e. the dynamics appear simultaneously in the two polarizations. In fig. 3(b) and (d) we depict the autocorrelation functions for the two of the polarization modes correspondingly. The PP dynamics in

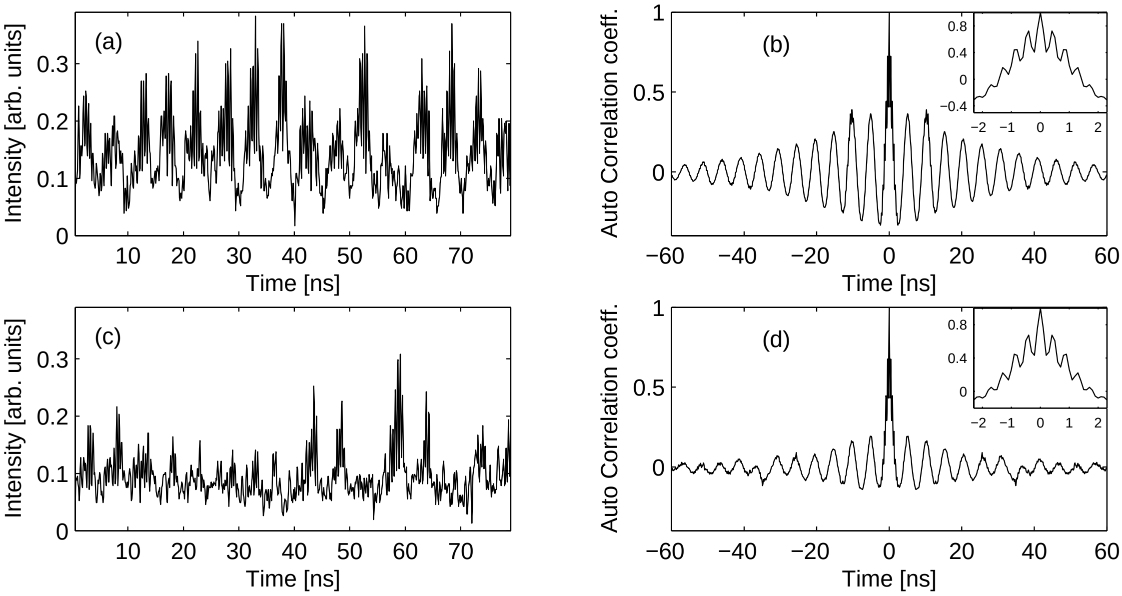

Figure 3: Polarization resolved dynamics of a VCSEL in PP regime. In (a) and (c) we plot time traces of a x-(y) polarized mode respectively. In (b) and (d) we plot the corresponding auto-correlation functions of the two polarization modes.

x-LP mode seems to be slightly better organized as the amplitude of the autocorrelation function is higher and the regularity is kept for much longer times (until more than 60ns). In the insets of figs. 3(b) and (d) we illustrate the presence of high intensity pulses appearing at the round trip time similar to the ones already shown in fig. 2(b) for the total intensity.

In some cases, the PP dynamics persists in one polarization mode only (in our case it is mostly the x-LP mode) and the second mode is in the off state. That type of dynamics, in which the pulses are emitted in one polarization only, corresponds to PP of type I. Here we demonstrate that there is also the possibility for the PP to occur in the two fundamental LP modes simultaneously. This type of dynamics we call PP of type II. In the PP of type II the amplitude of the PP is significantly lower than in the dynamics of type I. Similar interplay of the feedback induced complex dynamics and polarization mode competition has been found numerically by Sciamanna *et. al.* in [9] for the case of LFF and confirmed experimentally later on by Sondermann *et. al.* in [10].

In this paper, we have demonstrated the presence of PP dynamics for the case of VCSELs. The PP are observed in the total intensity of the emitted light as well as in the two fundamental LP modes. We have shown that the PP dynamics usually occur in the dominant polarization mode, defining type I PP dynamics but it also persists in both polarizations simultaneously indicating type II PP dynamics.

Acknowledgments

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