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TE-TM coupled mode dynamics in a semiconductor laser subject to feedback with variably rotated polarization

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ABSTRACT

We report on the experimental observation of dynamical collapses which address selectively the TM-mode of a laser subject to optical feedback with variably rotated polarization. Simultaneously, the TE-mode which remains the dominant lasing mode exhibits power bursts. We analyze the relative phase shift between the feedback fields into the TE- and TM-mode and find that the dynamical collapses, observed in a specific range of polarization rotation angles, can be attributed to large phase shift feedback conditions applied on the TM-mode.

A semiconductor laser (SL) subject to external polarization-rotated optical feedback has been proposed and studied as means to obtain an incoherent feedback. To fulfill this condition the optical feedback polarization is set to be orthogonal to the lasing (TE) mode of the cavity [1,2]. In this case the nonlinear dynamics emerge due to modulation of the laser's carrier density rather than its optical field as it occurs in conventional optical feedback. Such a system exhibits complex dynamics which received comprehensive attention in wide range of phase-space parameters [3–7]. The effect of polarization-rotated feedback has been also studied on vertical-cavity surface-emitting lasers which are known to naturally possess a polarization switching mechanism attributed to the cylindrical symmetry of such devices [8–12].

Feedback with variably rotated polarization mixes coherent and incoherent optical feedbacks and, when TM-mode power in the output of the solitary laser is non negligible, causes interesting TE-TM coupled mode dynamics. Feedback with variably rotated polarization can force an external cavity laser to oscillate in TE, TM or elliptical polarization modes [13] but no dynamics has yet been reported to the best of our knowledge.

In this paper, we report on the observation of dynamical collapses which address selectively the TM-mode of the laser in a specific range of the external feedback polarization rotation angles. Simultaneously, the TE-mode, which remains the dominant lasing mode of the laser, exhibits power bursts that are stronger than the power drops in the TM-mode while the total power of the laser shows net increase for short times. By means of a simple geometrical model we show that this dynamical instability occurs in the vicinity of a specific feedback polarization angle for which the feedback strength into the original TE (TM)-mode reaches its minimum (maximum). We attribute this behavior to destructive interference between the TM-mode and the feedback field.

In the experiments (see Fig. 1) we use two edge emitting SLs: Hitachi HL6501MG and Eudyna FLD6A2TK, referred to as laser 1 and 2, respectively. We operate the lasers close to maximum power (90 (35) mW for laser 1 (2)) which requires the driving currents to be well above threshold. The laser is collimated by a short focal length lens close to the output facet (not shown in Fig. 1). An optical feedback is achieved by introducing a mirror 2.3 m away that reflects back the output power of the laser. An additional lens is located in front of the mirror at about a focal length distance and is mounted on an XYZ translation stage to improve modematching of the feedback beam profile onto the front facet of the SL, therefore enhancing feedback power. We apply strong optical feedback which corresponds to a reduction in laser threshold current by 24.5% for laser 1 and 32% for laser 2 (measured with no feedback polarization rotation). The optical feedback path includes a quarter-wave plate (half-wave plate for double-pass feedback light) to allow flexible polarization rotation by any angle. A thick glass plate is used to output couple part of the laser power for the study of the emission properties.

The TE (TM) field stands for the linearly polarized mode of which polarization axis is parallel (perpendicular) to the semiconductor junction. Usually the TE-mode is the dominant lasing mode while the TM-mode is suppressed. However, for both lasers used in the setup, the TM-mode is relatively strong and easily detectable. For laser 1, in solitary configuration, the TE/TM laser power ratio is $P_{TE}/P_{TM} = 6$ and for laser 2 it is $P_{TE}/P_{TM} = 16$. To distinguish between these modes we split the output coupled signal by a polarization beam splitter and measure both ports simultaneously by two independent fast detectors monitored by a 600 MHz bandwidth digital oscilloscope (see Fig. 1).

In Fig. 2a and b, we show mean power measurements of the two modes as a function of the feedback polarization rotation angle θ.

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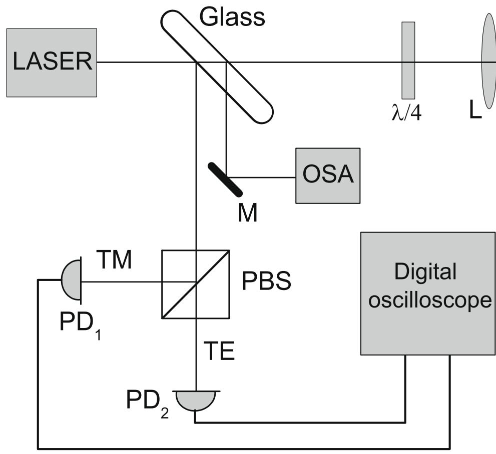

Fig. 1. Schematic representation of the experimental setup. A $\lambda/4$ waveplate in the optical feedback path allows for flexible polarization rotation to any angle. Polarization beam splitter (PBS) allows for simultaneous detection of TE and TM-modes of the laser; OSA – optical spectrum analyzer; M – mirror; L – lens and PD – photodetector.

Both figures share two common features which are essentially the subject of the present discussion. First, at a specific angle the TE (TM)-mode mean power reaches its minimum (maximum). We refer to this angle as a critical angle and it's value can be simply related to the ellipticity of the output polarization. Second, the behavior of the TE- and the TM-modes mean powers show strong asymmetry in respect to the critical angle. A smooth behavior on its one side is swapped by a sharp change on its other side. This symmetry breaking is related to the emergence of dynamical collapses of TM-mode and power bursts of the TE-mode.

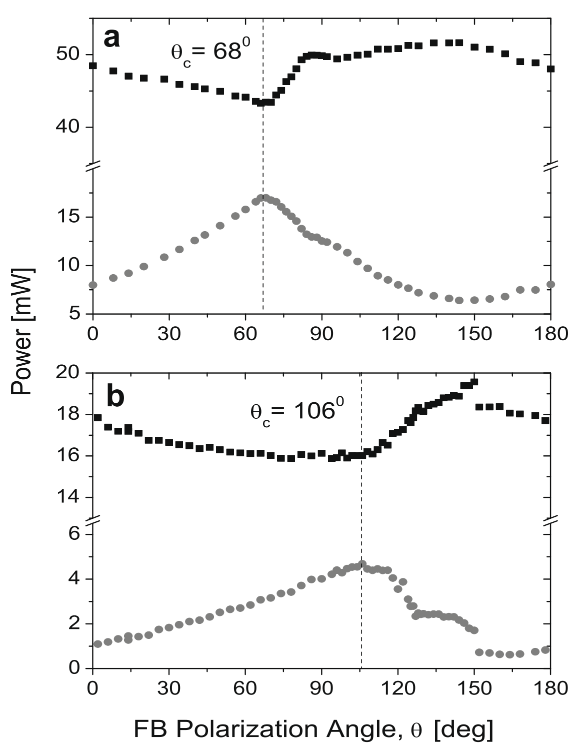

Fig. 2. Mean power of laser 1 (a) and laser 2 (b) as a function of feedback polarization rotation angle. Black squares stand for the TM-mode and gray circles are for the TE-mode. Critical angles for both lasers are marked by dashed lines.

Let us first discuss the conditions that yield the critical angle θ_C (see Fig. 2). As the phase shift between the TE and the TM laser fields is generally different from zero due to birefringence of the gain medium, the resulted output polarization is expected to be elliptical. This simple fact is verified experimentally for lasers 1 and 2 in both solitary and external feedback configurations. We stress that the birefringence of the gain medium does not lead to different wavelengths of TE and TM fields. This is a complex scheme that cannot be simply decomposed into two linearly polarized modes as if they are two independent lasers. SLs have been shown to possess elliptically polarized output in a similar type of setup [13]. We experimentally verified, for both lasers, that the optical spectra of TE- and TM-modes are indeed identical up to the resolution limit of the wavemeter (0.1 nm). It is also worth noting that the spontaneous emission spectra of TE- and TM-modes are different with central frequencies separated by ~6 nm, but this is no more the case for above threshold lasing conditions. We, thus refer to the output field of the laser as time independent elliptically polarized field.

We now argue that θ_C is obtained when the feedback field projection onto the original TE (TM) axis of the laser, referred to as TE (TM)-feedback, reaches its minimum (maximum) value. To fulfill this condition the polarization ellipse has to be rotated by an angle in which its major axis coincides with the TM axis of the laser. To verify the suggestion we determine the elliptical polarization of the laser at θ_C through measurement of the Stokes parameters [14] and find it to be in excellent agreement with the critical angle.

Note that the coherence lengths of the lasers, measured in free space by a Mach-Zehnder interferometer, are found to be significantly shorter ($\sim 100\ \mu m$) than the external cavity length in the vicinity of the critical angle [15]. This fact stands in apparent contradiction with the above discussion which relies on coherence between the TE-TM feedbacks and the laser's output fields. To resolve this issue we recall that the laser's rear facet is a common mirror for both the internal and the external cavities. This boundary condition imposes full coherence at the rear facet which extends into the gain medium of the SL.

Let us turn now to discuss the second feature of Fig. 2, which is the asymmetry of mean powers in respect to the critical angle. From the experimental point of view it is explained by the onset of TE-TM coupled mode dynamics. In Fig. 3 time resolved sequences of both lasers are shown. When the feedback rotation angle approaches θ_C from one side, rare events of TM-mode power collapses accompanied by bursts in the TE-mode become visible (see Fig. 3a and b). They are still rare and short and hardly affect the lasers' mean powers. When the critical angle is reached the events become frequent (see Fig. 3c and d) and as the feedback polarization is rotated further these events become even more frequent with significant revival times (see Fig. 3e and f). At this point the mean time interval between events is measured to be few hundreds of nsec. Fig. 3g and h zooms in on a collapse event and draws some similarity between the observed sequences and those known as low frequency fluctuations (LFF) [16,17]. The TM-mode collapses occur suddenly and are followed by slow, step-like revivals with time periodicity equal to the external cavity length (laser 1) or its multiples (laser 2). Note that the dynamic collapses address selectively the TM-mode. At the critical angle TM-mode power attains ~30% of the total laser power, thus its sudden collapse release significant amount of carriers to the benefit of the TE-mode which exhibits power bursts. When the feedback polarization is rotated further the events slowly disappear (see Fig. 3i and j).

As the observed features occur in the vicinity of the critical angle, let us consider the relative phase shift between TE- and TM-feedback fields when the feedback polarization rotation angle θ goes through θ_C. This phase shift can be readily obtained by a straightforward calculation which yields:

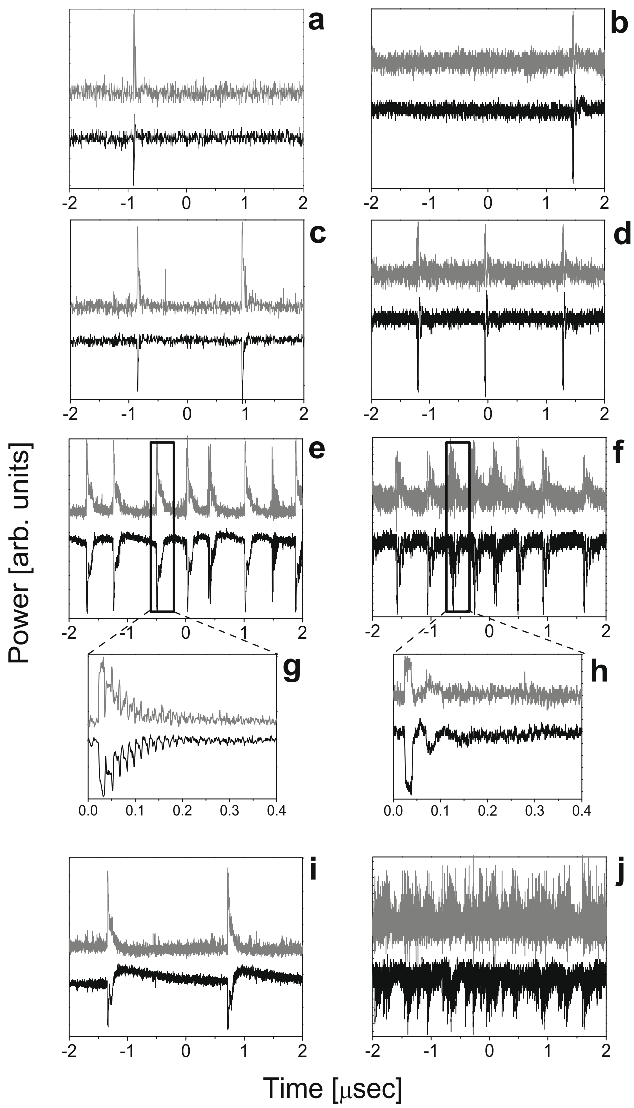

Fig. 3. Measurements of laser 1 (left column) and laser 2 (right column) powers with high time resolution for a number of feedback polarization rotation angles θ. Black (gray) line stands for TM(TE)-mode. Laser 1: (a) 65°; (c) $\theta_C = 68°$; (e) 78°; (i) 100°. Laser 2: (b) 96°; (d) $\theta_C = 106°$; (f) 110°; (j) 125° (g) and (h) are zoom-ins on the dynamic collapse events in (e) and (f), respectively.

$$\phi_{FB} = \arctan\left(\frac{\sin(\phi)}{\cos(\phi) - A\tan(\theta)}\right) - \arctan\left(\frac{\sin(\phi)}{\cos(\phi) + A\cot(\theta)}\right) \quad (1)$$

where $A = E_{TM}/E_{TE}$ and $E_{TM}(E_{TE})$ stands for the TM (TE) field amplitude, ϕ is the phase shift between E_{TM} and E_{TE} as they leave the internal cavity of the laser and ϕ_{FB} is the phase shift between TM- and TE-feedbacks as they come back. Note that A also depends on θ (see Fig. 2) but in the vicinity of the critical angle this dependence can be neglected up to the second order in θ. At θ_C, $\phi_{FB} = \pi/2$ and it is independent of ϕ and A. This agrees with the critical angle interpretation in which the ellipse main axes coincide with the TE-TM axes of the laser. Moreover, the gradient of ϕ_{FB} becomes maximal at θ_C. Thus when θ goes through the critical angle ϕ_{FB} crosses $\pi/2$ and approaches rapidly ϕ (or $\phi + \pi/2$ in the opposite direction) where fully constructive (destructive) interference condition with both (one of the) lasing fields is met. Apparently it is the TM-mode that suffers a large phase shift feedback condition [18] (in the case of destructive interference) and thus exhibits dynamical instabilities. When the TM-mode collapses the change in field amplitudes causes a change in the polarization ellipse and thus the obstacle that fails the TM-mode is removed until it grows back to full power and again approaches the large phase shift condition.

In conclusion, we show experimentally a selective dynamical collapse of TM-mode observed in a semiconductor laser subject to external feedback with variably rotated polarization. We identify a critical angle at which minimum (maximum) TE-(TM)-feedback is achieved. A simple geometrical model which relates θ_C to the parameters of the initial elliptical polarization is developed and confirmed experimentally. Based on this model dynamical collapses are attributed to the large phase shift feedback field conditions applied selectively on the TM-mode. We note that the described novel regime of external feedbacks is rich in multi-longitudinal mode dynamics which are beyond the scope of the present discussion. In particular, large splitting of the optical spectrum and antiphase dynamics of groups of longitudinal modes will be reported elsewhere.

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