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Multimode optical feedback dynamics of InAs/GaAs quantum-dot lasers emitting on different lasing states

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Quantum dot lasers are envisioned to be the next generation of optical transmitters used for short-reach communication links, owing to their low threshold current and high temperature operation. However, in a context of steady increase in both speed and reach, quantum dot lasers emitting on their upper energy levels have been recently of greater interest as they are touted for their faster modulation dynamics. This work aims at further evaluating the potential impact of such lasers in communication links by characterizing their long-delay optical feedback responses as well as the role of the lasing states on the multimode dynamics of InAs/GaAs quantum-dot Fabry-Perot devices sharing the same design. Results unveil that the excited-state laser shows a much larger sensitivity to optical feedback, with a more complex route to chaos, and a first destabilization point occurring at lower feedback strengths than for a comparable ground-state laser, which remains almost unaffected. [http://dx.doi.org/10.1063/1.4973335]

In order to meet the requirements of the explosive growth in data traffic, fast and low-cost transmitters with low energy consumption are required in particular for short-reach communication links such as access, metro, and data-center optical networks.[1,2] Owing to their enhanced quantum size effect, InAs/GaAs quantum dot (QD) lasers made by self-organized nanostructures are one of the best practical examples of emerging nanotechnologies hence allowing ultra-low threshold current and high temperature operations.[3–5] Very recently, it was proved that QDs have high potential to overcome the inherent problems related to standard diode lasers integrated on silicon in the context of large-scale and low-cost photonic integration.[6–8] In this context, a 200 Gbps QD-laser-based datacenter interconnect platform has been recently launched with the aim at achieving 400 Gbps in the future.[9] Usually it is known that QD lasers operating on the ground-state (GS) transition exhibit a larger resistance to external optical feedback which is of paramount importance for isolator-free applications.[10,11] However, this enhanced robustness to optical perturbations which is mainly due to the large damping of the relaxation oscillations also sets the limit of the laser's modulation capabilities to few GHz at room temperature.[11,12] In order to increase both speed and reach, prior arts have proposed to take advantage of stimulated emission originating from the excited states (ESs) transitions.[13] Owing to the faster carrier capture from the surrounding carrier reservoir as well as a higher saturated gain,[14] ES QD transmitters have been touted to be a promising solution for high-speed applications.[15,16] The larger degeneracy of the ES translates into a larger differential gain and smaller nonlinear gain compression than to those of the GS. The first successful investigation at the link level was realized with 1.3-μm

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InAs/GaAs QD lasers emitting on the first ES transition, for which modulation capabilities up to 25 Gbps (OOK) and 35 Gbps (PAM) have been reported.[17,18] Prior studies have also pointed out that taking advantage of the ES can be useful for ultra-short pulse generation[19,20] and that the dynamics of ES QD mode-locked lasers in presence of optical feedback is more stable owing to a smaller linewidth enhancement factor (LEF).[21] Very recently, both theoretical and experimental works have proved that ES QD lasers can indeed exhibit a near-zero LEF in comparison with the GS ones, which is of first importance for the realization of chirpfree transmitters as well as crucial regarding the laser coherence and the modal stability.[13,22] Lastly, various studies have investigated the two-state lasing dynamics where ES and GS lasing can take place simultaneously either with or without external optical feedback.[21,23–25] In particular, it was recently unveiled that the two-state lasing can produce a large GS modulation enhancement.[26–28] In order to further evaluate the potential impact of such lasers in the view of their inclusions into a fiber-pigtailed telecom module, this work aims at characterizing the long-delay optical feedback dynamics of InAs/GaAs QD Fabry-Perot (FP) lasers emitting either on the sole GS or exclusively on the ES. Surprisingly, experiments unveil an accelerated route to chaos with ES lasers, and a destabilization scenario occurring at much lower feedback strength than for a comparable GS laser, the latter remaining almost unperturbed. We thus believe that this analysis gives insights on the QD lasing states dynamics under optical feedback, which is of first importance for the development of future high-speed QD transmitters for isolator-free applications.

Both devices studied share the exact same amplifying medium and cavity design. The cavity is 1 mm long with a 2 μm-wide waveguide, and the active region is based on a dots-in-a-well structure including 10 InAs QD layers grown by molecular beam epitaxy (MBE) embedded in InGaAs quantum wells.[29] The optical spectra of both lasers are shown in FIG. 1 (a) and (b), their LI curves being represented in the insets. At room temperature (293 K), the GS laser has a threshold current I_{th} of 16.5 mA, a differential external quantum efficiency of 21%, and a gain peak around 1300 nm. The ES lasers threshold current is 88.5 mA with a differential external quantum efficiency of 11%, and a gain peak around 1220 nm. Practically, emission on the ES state only can be achieved in multiple ways such as increasing the pump current to reach the ES threshold or preventing the GS stimulated emission by shortening the cavity length, coating the facets or via the use of a dichroic mirror.[17] In this work, the GS/ES emission lines are selected by exploiting the natural wavelength dispersion of the photoluminescence peak across the wafer, ensuring that GS emission is naturally inhibited for the ES laser. As opposed to Ref. 30 where devices with different laser cavity lengths were studied, this study goes a step beyond and investigates the multimode dynamics of the two radiative transitions of InAs/GaAs QD lasers having the same electronic structures and sharing the same amplifying medium, with the same cavity dimensions. The QD lasers are inserted into a 7 m long external fibered optical feedback loop as represented in FIG. 2.

The laser emission is coupled by an AR coated lens-ended fiber, and split into feedback and detection paths by a 90/10 a fiber coupler. In the feedback path, the emission is reflected back to the QD by a back-reflector (BKR) integrating a variable attenuator. The polarization controller in the feedback path allows matching the polarizations of the emitted and reflected light in order to maximize the effects of the optical feedback. Due to the different output divergence of both devices,

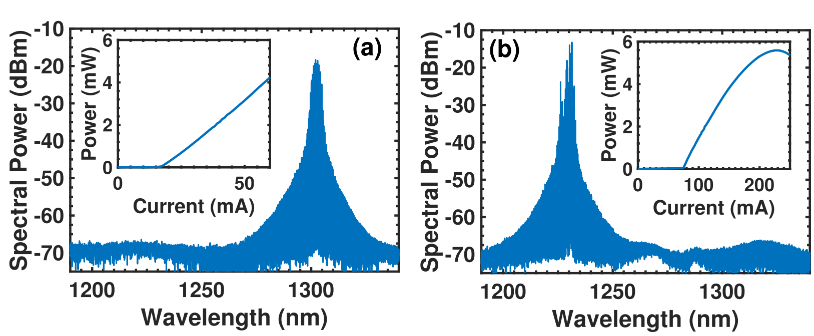

FIG. 1. Optical spectra of (a) GS laser and (b) ES laser at 2 $\times I_{th}$, the insets represent the LI curves of the GS and ES lasers respectively.

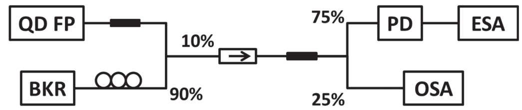

FIG. 2. Experimental setup used for the long-delay feedback measurements (QD FP: Quantum Dot Fabry-Perot Laser; PD: Photodiode; OSA: Optical Spectrum Analyzer; ESA: Electrical Spectral Analyzer; BKR: Back-Reflector).

the maximal attainable feedback strength r_{ext} differs for both devices. For the GS laser, r_{ext} ranges from 0% to ≈ 5.9%, while it only goes up to ≈ 4.6% for the ES one. The multimode feedback dynamics are analyzed with electrical and optical spectrum analyzers (ESA and OSA) at the end of the detection path. Since the external cavity length is of several meters, the impact of the phase of the delayed field is neglected.

The optical feedback dynamics of the GS laser are first investigated. While bias conditions of 1.5×, 2.5× and 3×I_{th} (25, 33 and 50 mA resp.) were considered, the GS laser remains stable for the whole range of currents and feedback strengths studied, only a small red-shift of the FP modes was observed with no sign of spectral broadening. FIG. 3 represents optical and electrical spectra recorded at 3×I_{th}, without feedback (solitary case e.g. r_{ext}=0) and for the maximal feedback strength (r_{ext}=5.9%).

This increased feedback resistance of the GS lasing has already been reported several times and attributed to the large damping rate of the relaxation oscillations.[4,10,11] As for the ES laser, the bias conditions were fixed to 1.5× and 2×I_{th} (133 and 177 mA resp.). Due to the rollover observed in the output power above 180 mA (see the inset of FIG. 1 (b)), higher bias currents were not considered. FIG. 4 represents a mapping of optical and electrical spectra of the ES laser measured as a function of r_{ext} under different bias currents. At 1.5×I_{th}, the laser is found to be almost insensitive to optical feedback up to 0.4% of feedback, beyond which the modes broaden (FIG. 4 (a) and (b)).

FIG. 5 presents a set of optical and electrical spectra recorded at both bias levels for the ES laser in solitary operation, as well as under low and maximal optical feedback. FIG. 5 (a) and (c) illustrate the mode broadening in the optical spectrum for both pumping levels, while FIG. 5 (b) and (d) depict the destabilization in the electrical spectrum. In particular, FIG. 5 (b) shows that around 0.6% of optical feedback, quasi-periodic oscillations with a high pedestal take place. At maximum feedback strength, broadband spectrum with no clear peaks is observed that is a characteristic of chaotic behaviors. Besides, at higher bias currents and similar feedback strengths, no quasi-periodic dynamics is observed as shown in FIG. 5 (d). In addition, the comparison between FIG. 5 (b) and (d) unveils that chaos is intensified at higher pump and exhibits a larger bandwidth. In contrast to distributed feedback (DFB) lasers, for which a better stability against optical feedback is observed at larger bias currents,[31,32] we found here that the destabilization of FP lasers may be more complex due to modal competition. Finally, at higher pump levels, the ES laser appears even more sensitive to optical feedback since the critical feedback level beyond which the route to chaos occurs through

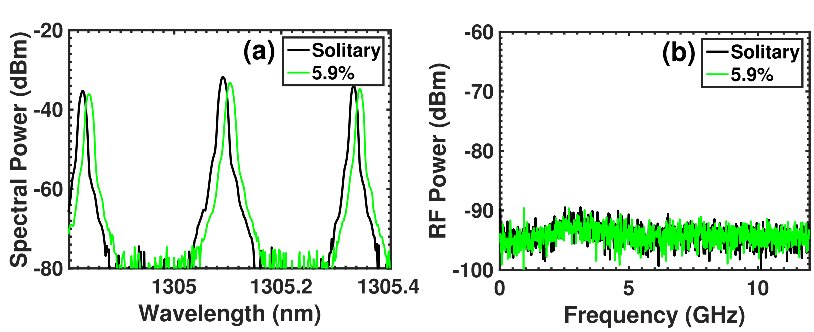

FIG. 3. (a) Optical and (b) electrical spectra of the GS laser measured at 3×I_{th} without feedback (solitary) and for the maximal feedback strength.

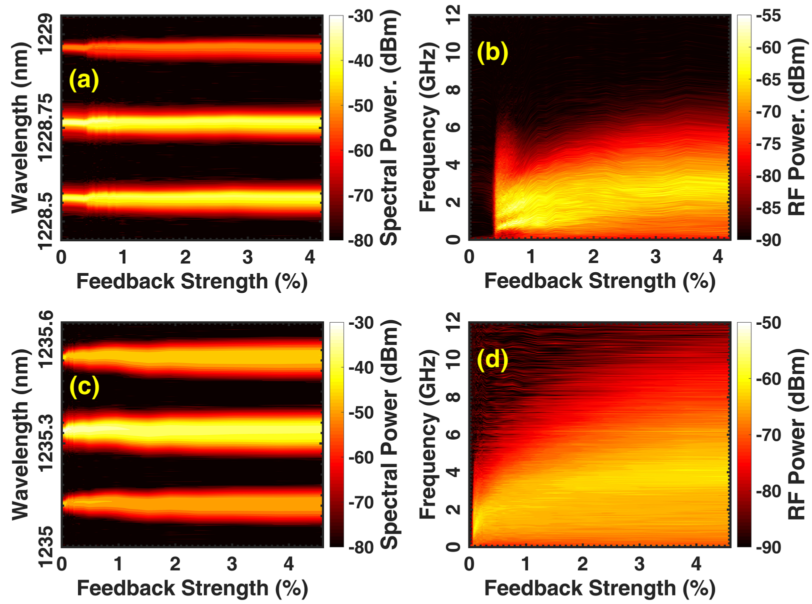

FIG. 4. ES laser: optical (left) and electrical (right) spectral mapping at (a-b) 1.5×I_{th}, (c-d) 2.5×I_{th}.

quasi-periodic oscillations drops down to 0.05% as opposed to 0.4% at lower bias. Once the quasi-periodic oscillations window disappears, the laser directly oscillates chaotically.

A straightforward method to analyze the differences in the feedback sensitivity is to estimate the damping rate from the expression of the critical feedback level $r_{ext,c}$:[10,32]

$$r_{ext,c} = \Gamma^2 \frac{\tau_i^2}{16C^2} \frac{1+\alpha^2}{\alpha^4} \tag{1}$$

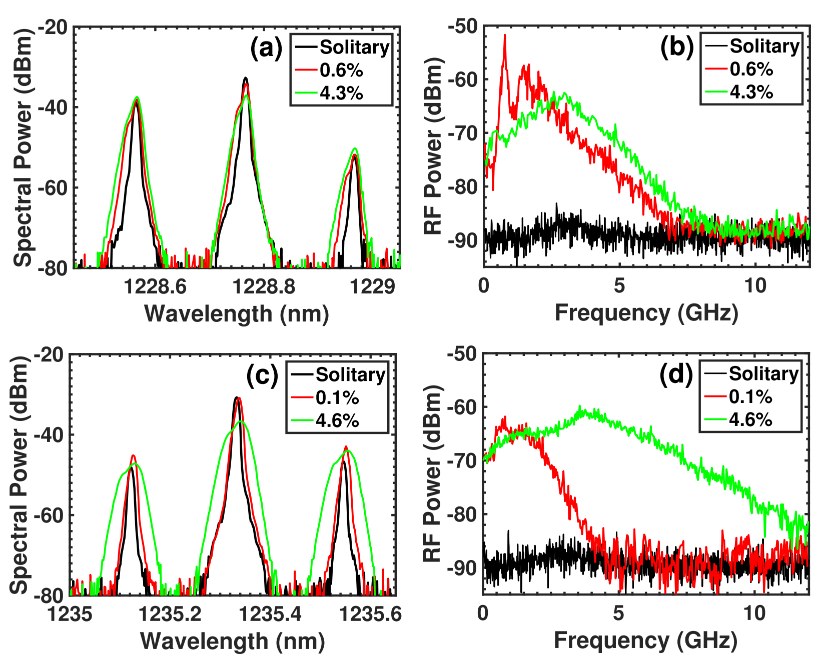

FIG. 5. ES QD laser at 1.5×I_{th} bias level: (a) optical and (b) electrical spectra of the solitary laser, at 0.6% and 4.3% optical feedback; ES laser at 2.5×I_{th} bias level: (c) optical and (d) electrical spectra of the solitary, at 0.1% and 4.6% optical feedback.

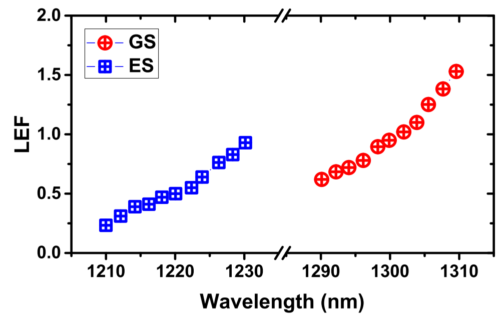

FIG. 6. The below-threshold LEF spectral variations for the GS and ES QD lasers.

where τ_i is the photon round-trip time within the laser cavity, α the LEF of the laser under consideration, and C the external coupling coefficient whose expression for a FP laser is given by $C = (1 - R)/2\sqrt{R}$, with R the facet reflectivity. As the GS laser is always found stable, a lower boundary for the critical feedback is assumed to be the maximum feedback level, hence $r_{ext,c} > 5.9\%$. The LEF is retrieved from the wavelength shift and gain change with respect to the current increase. FIG. 6 represents spectra of LEF for both lasers. The red-shift due to thermal effects, measured by varying the pump current right above threshold, was subtracted from the blue-shift measured below threshold to only consider the refractive index variation due to changes in carrier density.[33] The below-threshold LEF spectral variation ranges from 0.25 to 1.0 for the GS laser (red) and from 0.5 to 1.5 for the ES one (blue). At the gain peak, LEF is found to be of 0.5 for the ES laser and around 1 for the GS laser.

From Eq. 1, and assuming R = 0.32, C = 0.6, τ_i = 21 ps, Γ_{ES} is estimated to be of 1.6 GHz and 0.6 GHz at 1.5× and 2×I_{th} while Γ_{GS} >18 GHz for the GS laser. The difference between the GS and ES emissions can be qualitatively explained by the QD carrier dynamics involving both capture and relaxation for the GS laser, unlike for the ES. While we show that the ES state alone exhibits dynamics similar to quantum well lasers under optical feedback, the extra carrier transports required for emission on the GS lead to a higher damping rate preventing oscillations under medium optical feedback. However, it has to be noted that the shapes of the gain spectra of both lasers may also affect the dynamics.[15,34] To this end, the ES laser under study might be more sensitive to optical feedback also because of a stronger modal competition as compared to the GS laser, which has a rather flat optical spectrum around the central lasing wavelength (not shown here). The different dynamics can also be attributed to the ES degeneracy where the existence of two closely spaced p-levels can lead to more radiative transitions.[35] Finally, although the LEF could have been measured beyond the laser's threshold, as a value of α larger than the sub-threshold one may be measured in the experimental bias conditions, this will not affect the order of magnitude of the damping rates extracted since their ratios would remain dominated by the square root of the ratio of the critical feedback levels.

In summary, this work investigates the multimode optical feedback dynamics of InAs/GaAs QD lasers emitting on only either the GS or the ES. Under long-delay optical feedback, the ES laser can easily be destabilized while the GS one remains unchanged. Although the ES laser is faster, its smaller damping rate combined to a stronger partition noise contribute to increase the sensitivity to external optical feedback. As a conclusion, this study is of prime importance for the understanding of QD laser dynamics and developing new guidelines regarding isolation requirements for short-reach communication links. Further work will investigate the case of GS/ES InAs/GaAs distributed feedback lasers.

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