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Recent advances in InAs/GaAs quantum dot lasers with short optical feedback

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ABSTRACT

The optical feedback dynamics of two multimode InAs/GaAs quantum dot lasers emitting exclusively on sole ground or excited lasing states is investigated under the short delay configuration. Although the two lasers are made from the same active medium, their responses to the external perturbation are found not much alike. By varying the feedback parameters, various periodic and chaotic oscillatory states are unveiled. The ground state laser is found to be much more resistant to optical feedback, benefiting from its strong relaxation oscillation damping. In contrast, the excited state laser can easily be driven into very complex dynamics. While the ground state laser is of importance for the development of isolator-free transmitters, the excited one is essential for applications taking advantages of chaos such as chaos lidar, chaos radar, and random number generation.

Keywords: Quantum dot lasers, optical feedback, dynamical states

1. INTRODUCTION

The nonlinear dynamics of semiconductor lasers operating under external optical feedback has been widely studied in the literature.¹ Indeed, by controlling the feedback strength and the external cavity length, multiple complex dynamical states and their routes to chaos can be observed.¹ Compared to quantum well (QW) lasers, significant breakthroughs have been achieved by using quantum dots (QD) as gain media^{2,3}. Their inherent properties allow producing energy- and cost-efficient devices with outstanding temperature stability, low threshold current, ultrafast gain dynamics, and low amplified spontaneous emission.³ A low threshold current density and high internal quantum efficiency results in a reduced amount of dissipated heat. Even at high operation temperatures, temperature insensitive threshold currents have been observed for p-doped devices.⁴ Most advantages of QD lasers have been demonstrated for InAs/GaAs QD lasers operating at 1310 nm, hence mostly targeting short communication links such as metro and access networks. QD lasers usually show three possible regimes of lasing operation, depending on the bias conditions: (i) ground state (GS) lasing; (ii) dual state emission showing an interplay dynamic between the GS and the first excited state (ES), and (iii) ES lasing^{5,6}. While feedback dynamics of QD lasers has been widely studied in particular in the context of the dual-state dynamics,⁷ none of this work focused on the feedback dynamics of QD devices emitting exclusively on single lasing states. Here, we report for the first time on the feedback dynamics of two InAs/GaAs QD Fabry-Perot (FP) lasers sharing the same active regions but emitting exclusively on either the GS or the ES. In other words, the QD lasers under study do not exhibit the GS-ES interplay dynamics where ES and GS lasing take place simultaneously. By varying the feedback strength under the short delay configuration, multiple dynamical states such as periodic (P), regular pulse package (RPP), quasi-chaos pulse package (QCPP), and chaotic (C) states are unveiled. The

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GS laser is found to be rather insensitive to optical feedback due to the large damping factor. In contrast, the ES laser can be driven more easily into complex dynamical regimes including chaotic states. We believe that these results are of primary importance for utilizing the nonlinear dynamics for ultrafast devices in particular for the development of isolator-free transmitters, integrated self-pulsating devices and other applications using diode laser chaos.⁸

2. LASER STRUCTURE AND EXPERIMENTAL SETUP

The dynamical characteristics of the two FP multimode QD lasers, one emitting exclusively on the GS and one on the ES, are investigated and compared under different operation and feedback conditions. For both lasers, their active regions comprise 10 InAs dot sheets grown in InGaAs QWs by molecular beam epitaxy (MBE) with a dot-in-well structure. The dot densities are around $3 \sim 5 \times 10^{10} \text{cm}^{-2}$ per layer and their lateral extensions approach 30 nm. Both laser types have internal cavities of 1 mm long and $2 \mu\text{m}$ waveguides etched through the active area. Lasers are left as-cleaved and cavity lengths are both 1 mm long while the ridge waveguide (RWG) etched through the active region is $2 \mu\text{m}$ wide. For the GS laser, the threshold current I_{th} is of 16.5 mA and the external efficiency is 21%. For the ES one, the threshold current I_{th} is of about 88 mA and the external efficiency is 11%. Figures 1(a) and 1(b) display the two optical spectra taken at 1.5 times the threshold. The first FP laser (in red) emits at $\sim 1300 \text{ nm}$ on the sole GS transition whereas the second (in blue) is at $\sim 1230 \text{ nm}$ on the sole ES transition. The insets highlight the center of the emission of both lasers respectively, where the ES one exhibits a modulated optical spectral envelope in contrast to the GS laser.⁹ In this work, the ES selection was obtained by exploiting the natural wavelength dispersion of the photoluminescence peak across the entire wafer.⁹ Figure

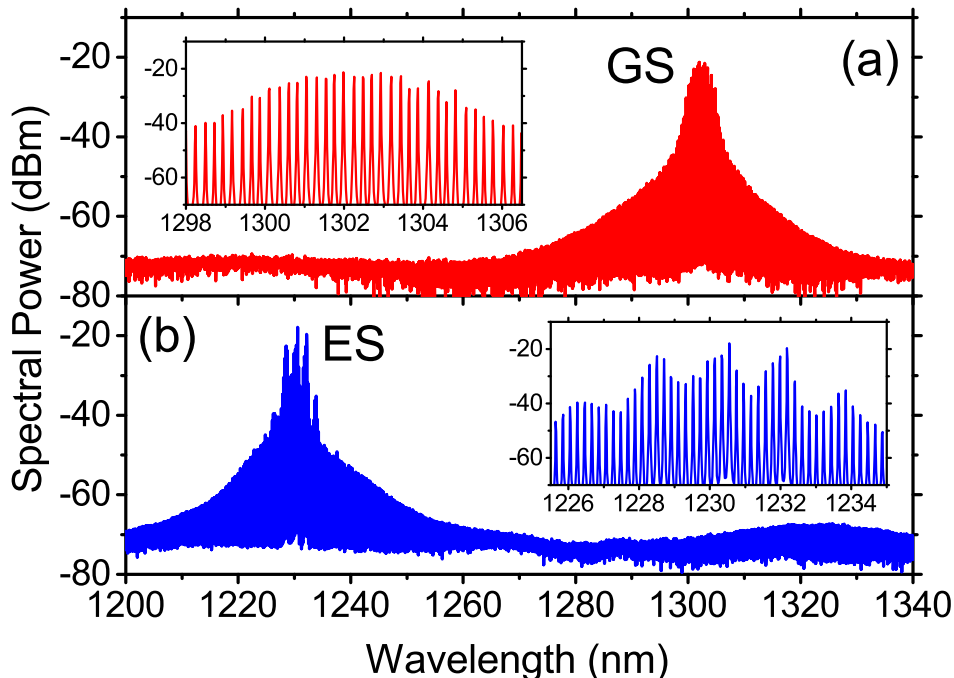


Figure 1. Optical spectra of the (a) GS and (b) ES lasers measured at 1.5 times the threshold under free-running condition (no feedback applied).

2 shows the schematic setup of the QD laser subject to optical feedback. The output of the laser towards the left is fed back to the laser cavity through a partially reflecting mirror to form an external cavity with length L_{ext} with a minimum cavity length of 2 cm. The ratio between the frequency of the external cavity f_{ext} and the relaxation oscillation frequency f_{RO} is such as $f_{ext}/f_{RO} > 1$ meaning that the short cavity regime is investigated in this paper. A variable optical attenuator is used to adjust the feedback strength ξ_f defined as the ratio of the feedback field to the laser output field. The optical signals are analyzed by an optical spectrum analyzer and

the optical power is measured by a power meter. The electrical signals are detected by two identical high-speed photodetectors and analyzed by an electrical spectrum analyzer and a real-time oscilloscope.

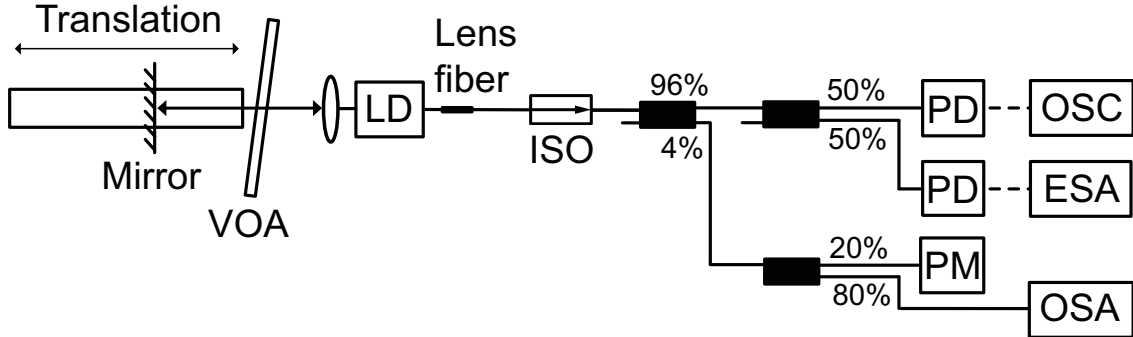


Figure 2. Experimental setup of a QD laser subject to optical feedback. LD: QD laser; ISO: isolator; PD: high-speed photodetector; ESA: electrical spectrum analyzer; OSA: optical spectrum analyzer; OSC: oscilloscope; PM: power meter.

3. RESULTS AND DISCUSSION

Figure 3 shows the time series and the corresponding power spectra of the dynamical states measured at 1.7 times the threshold for the GS laser. At $L_{\text{ext}} = 30$ mm, a RPP state is demonstrated in Figures 3(a) and 3(b) for $\xi_f = 0.826$. The RPP regime is a typical complex dynamics arising under optical feedback, which manifests as regular pulsations in the output power.¹⁰ It occurs in the very short cavity regime meaning that a very small

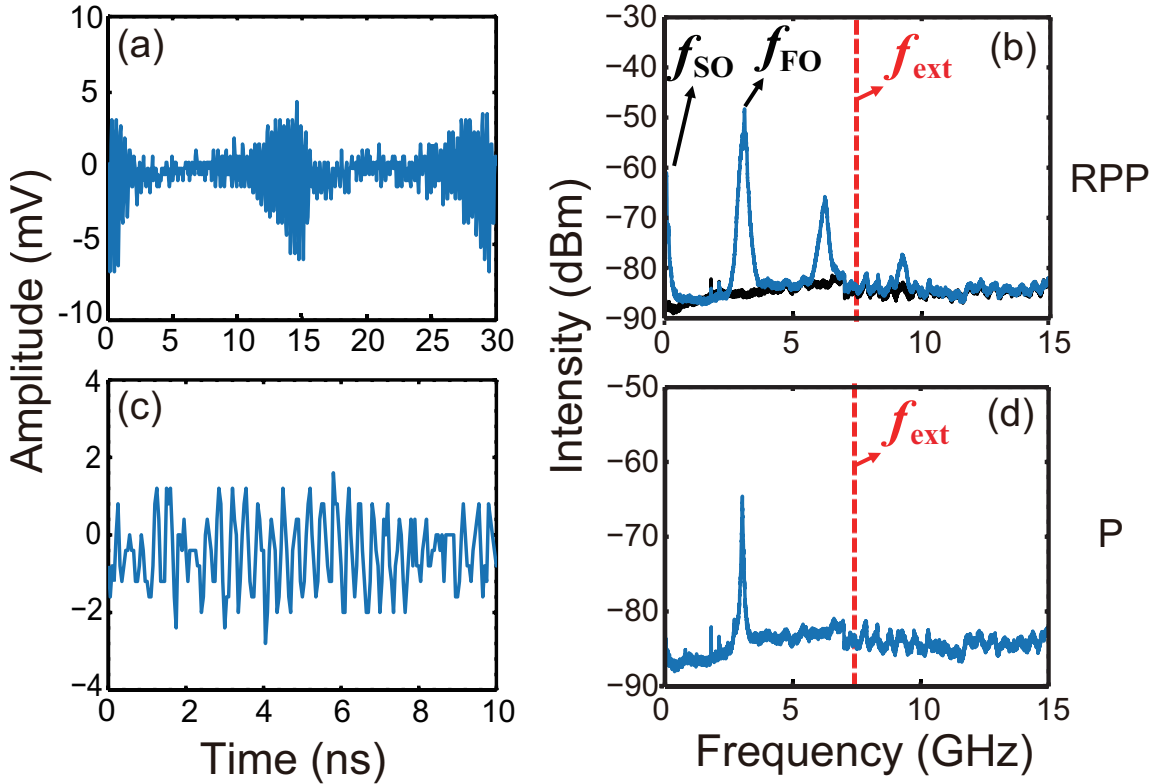


Figure 3. Time series and corresponding power spectra of the dynamical states measured at 1.7 times the threshold for the GS laser with $(\xi_f, L_{\text{ext}}) =$ (a)(b) (0.826, 30 mm), (c)(d) (0.731, 30 mm). Red-dashed lines depict the external cavity frequency f_{ext} and black curves are the spectra without feedback for reference.

number of modes is involved. Unlike the low-frequency fluctuation regime taking place when $f_{ext} \ll f_{RO}$, the path in the phase space for the RPP regime is one direction only, which means that the crisis is no longer present, and the trajectory always visits the same external cavity modes leading to the birth of fast and regular oscillations at f_{ext} . Different from the RPP state described in¹⁰ for QW lasers showing a fast oscillation frequency f_{FO} that coincides with f_{ext} , the RPP state observed in this work has f_{FO} around $f_{RO} = 3$ GHz instead. This difference might be attributed to the fact the QD laser does not operate in the ultra short cavity regime for which $f_{ext} \gg f_{RO}$, but rather in a short delay configuration for which the relaxation oscillation frequency remains still pretty close to the external cavity frequency. In addition, it has to be stressed that the slow oscillation has a frequency $f_{SO} = 72$ MHz that is much lower than both f_{ext} and f_{RO} . Last but not the least, as compared to the RPP states reported in¹⁰ with less than 10 oscillations in each package, more than 40 oscillations are packed in the RPP states found in this GS laser. Figure 4 shows the evolution of f_{SO} as a function of the external cavity frequency for two values of the bias current namely 1.5 times and 1.7 times the threshold respectively. Results show that there is a slight dependence of the slow oscillation with the bias current which is in agreement with prior works on the RPP regime in QW lasers^{11,12}. For instance, for an external cavity frequency, experiments show that f_{SO} increases by about 20 MHz with the bias current. To the best of our knowledge, this RPP regime has never been observed so far in QD lasers.

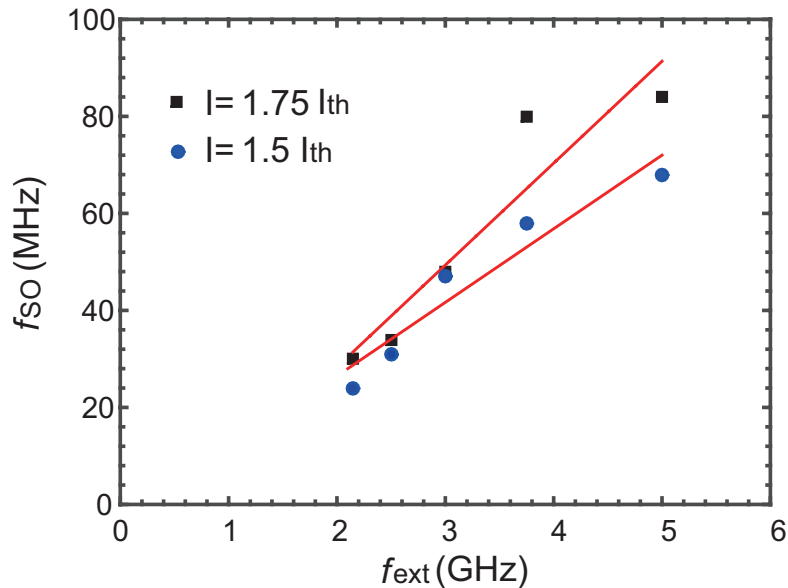


Figure 4. Evolution of the SO frequency f_{SO} measured in the RPP regime for the GS laser at 1.5 times and 1.7 times the threshold respectively.

When ξ_f decreases to 0.731, the laser becomes more stable and a P state oscillating at f_{RO} is found as shown in Figures 4(c) and 4(d) is found. Further increase of the external cavity length to the long cavity regime leads to frequency-locking regimes as reported elsewhere.¹³ Experimental results reveal that the GS laser is perfectly stable such that no chaotic state was found whatever the feedback strength level used in this setup. Besides, the GS laser remains under the steady-state condition providing the feedback strength does not exceed 30% which is already much larger compared to any typical reflection levels taking place in a transmission system^{13,14}.

Figure 5 shows the time series and corresponding power spectra of the dynamical states from the ES laser still measured at 1.7 times the threshold. With $L_{ext} = 20$ mm and with a strong feedback of $\xi_f = 0.703$, a C state with irregular intensity modulation and a spectrum broadly elevated from the noise floor is shown in Figures 5(a) and 5(b). When ξ_f decreases to 0.686, a QCPP state is found and shown in Figures 5(c) and 5(d). Different from a RPP state that has a fast oscillation at f_{ext} ,¹⁰ the fast oscillation of this QCPP oscillates at f_{RO} . The f_{SO} does not coincide with either f_{RO} or f_{ext} but with a frequency of 340 MHz instead. Moreover, unlike the spectra of typical RPP states that have frequency components of only fast or slow oscillations and their corresponding harmonics and beats, the spectrum of the QCPP state preserves the broadband characteristics as present in the

C state. When ξ_f further decreases to 0.48, as shown in Figures 5(e) and 5(f), a P state stably oscillating at $f_{FO} = 4$ GHz is obtained. Finally, let us stress that in the long cavity regime, more complex dynamical states are observable in the ES laser hence leading to a complete route to chaos¹³ which which is fundamentally different than the dynamics displayed in the GS laser.

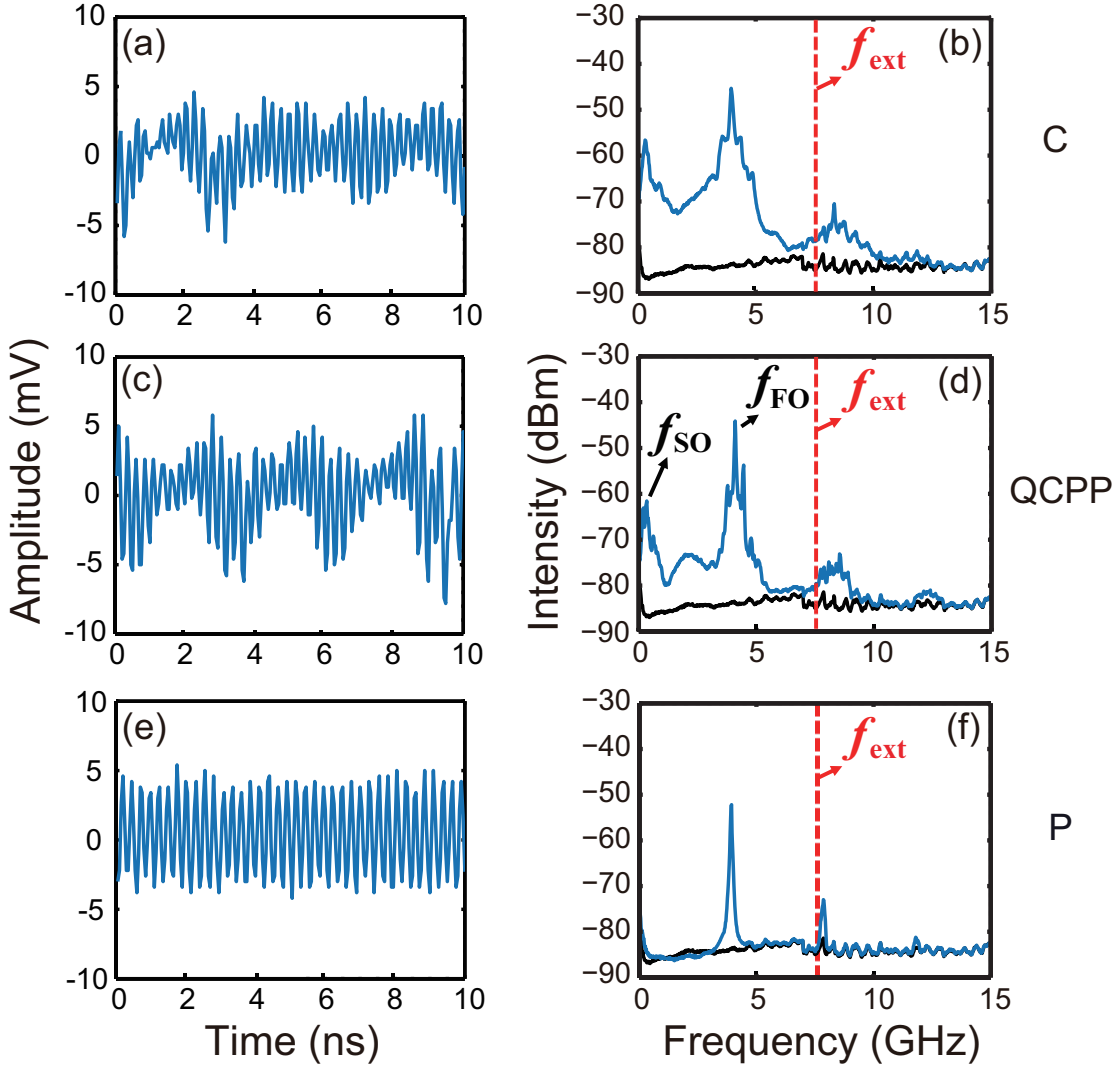


Figure 5. Time series and corresponding power spectra of the dynamical states measured at 1.7 times the threshold for the ES laser with $(\xi_f, L_{\text{ext}}) =$ (a)(b) (0.703, 20 mm), (c)(d) (0.686, 20 mm), (e)(f)(0.48, 20 mm). Red-dashed lines depict the external cavity frequency f_{ext} and black curves are the spectra without feedback for reference.

Figures 6 show f_{SO} extracted from the RPP states of the GS laser and the QCPP states of the ES laser under different f_{ext} . As can be seen, while f_{SO} does not coincide exactly with either f_{RO} or f_{ext} , f_{SO} in both states increases linearly as f_{ext} increases.

Compared to the GS laser which is in general stable and insensitive to feedback, the ES laser is more easily moving to complex dynamics. While a GS laser is of large importance for the development of isolator-free transmitters in short-reach networks, an ES laser on the other hand can be essential for applications taking advantages of chaos such as chaos lidars, chaos radars, and high-speed random number generations.¹⁵⁻¹⁸ From these results it is obvious that, although the GS and ES lasers have the same active medium, their response to the feedback are very different. Unlike the ES laser, the carrier dynamics of the GS laser involves transport, capture, and relaxation, leading to a larger damping rate that stabilizes the laser and prevents the development

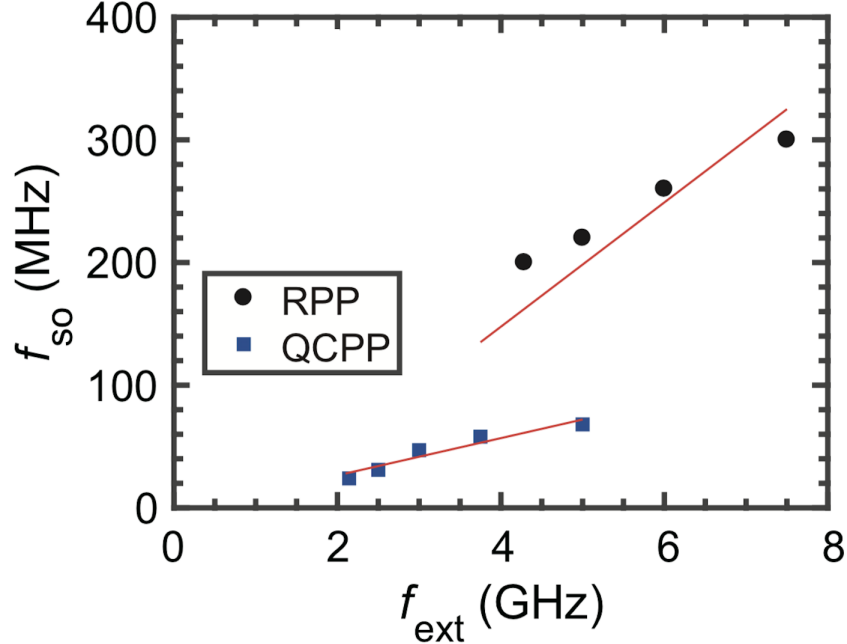


Figure 6. Slow oscillation frequencies f_{SO} of the RPP and QCPP states under different external cavity frequencies f_{ext} of both GS and ES lasers respectively. Red lines are the linear fits.

of complex dynamics. As reported in,⁹ the damping is as large as 18 GHz for the GS laser whereas it is below 1 GHz for the ES one. Moreover, the ES laser has a stronger modal competition⁹ which also makes it easier to be driven into instabilities.

4. CONCLUSIONS

This work investigates for the first time the dynamical states and their spectral characteristics of optical feedback InAs/GaAs QD lasers emitting exclusively on single lasing states in the short cavity regime. Although the GS and ES QD lasers are made from the same active medium, their feedback dynamics are found not much alike. The GS laser is shown to be almost insensitive to feedback, especially at higher bias levels. No chaotic states was found which is of vital importance for the development of high-speed transmission links operating without isolator, in agreement with some earliest results. In contrast, the ES laser exhibits a plethora of complex dynamics including chaotic states, especially at higher bias levels, thus being useful for integrated self-pulsating devices, chaotic lidars and radars as well as high-speed random bit generations.

5. ACKNOWLEDGMENTS

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