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Bozhang Dong, Jun-Da Chen, Fan-Yi Lin, Justin C. Norman, John E. Bowers, and Frédéric Grillot

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Dynamic and nonlinear properties of epitaxial quantum dot lasers on silicon operating under long- and short cavity feedback conditions for photonics integrated circuits

Bozhang Dong*

*LTCI, Télécom Paris, Institut Polytechnique de Paris,
19 Place Marguerite Perey, 91120 Palaiseau, France*

Jun-Da Chen and Fan-Yi Lin

*Institute of Photonics Technologies, Department of Electrical Engineering,
National Tsing Hua University, Hsinchu 300, Taiwan*

Justin C. Norman and John E. Bowers

*Department of Electrical and Computer Engineering,
University of California, Santa Barbara, California 93106, USA*

Frédéric Grillot[†]

*LTCI, Télécom Paris, Institut Polytechnique de Paris,
19 Place Marguerite Perey, 91120 Palaiseau, France and
Center for High Technology Materials, University of New-Mexico, Albuquerque, New-Mexico, 87106, USA
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This work reports on an investigation of the dynamics of 1.3 μm epitaxial quantum dot (QD) lasers on silicon subject to delayed optical feedback. Operating the device under different feedback conditions, we experimentally identify various dynamical states of periodic oscillations. In the long-cavity feedback regime, the device remains chaos-free up to $\sim 70\%$ (-1.55 dB) feedback strength. This remarkable result is in agreement with prior studies and is attributed to the particular design and properties of the QD-based active region. Shortening the external cavity length to the short-cavity regime being on the scale of photonics integrated circuits (PICs), the onset of periodic oscillations only takes place under extremely high feedback strength, which is much higher than those in PICs. The devices studied exhibit strong resistance to chip-scale back reflections in absence of any unstable oscillation. Our results also demonstrate that p-doping is an efficient technique to further improve the feedback tolerance. These results point out the potential of QD lasers as an on-chip light source not requiring an optical isolator and gives insights for developing ultra-stable silicon transmitters for PIC applications.

I. INTRODUCTION

Monolithic photonic integration is important for compact, robust and energy-efficient transceivers, which are important for the high-speed telecommunication industry, next generation datacom transceivers [1, 2] and advanced LIDAR systems [3] applied to self-driving automobiles [4]. In particular, silicon photonics benefits from the mature complementary-metal-oxide-semiconductor (CMOS) industry and paves the way for low-cost, small-footprint and large-scale photonic integrated circuits (PICs) [5]. Due to the charge carrier confinement in three spatial dimensions, quantum dots (QDs) used as a gain media can offer superior continuous wave properties over their quantum well (QW) and bulk counterparts [6, 7], which make them highly interesting for PIC applications. Recent studies have demonstrated that QD lasers directly grown on silicon substrates exhibit high performance with low threshold current [8], high gain properties [9], remarkable temperature stability [10], low

relative intensity noise (RIN) [11, 12] and large reflection insensitivity [13, 14]. All those features are of paramount importance for the integration of stable and isolator-free silicon based transmitters in PICs with error-free transmission [7, 13].

The nonlinear dynamics of semiconductor lasers subject to external optical feedback has been intensively studied. Prior studies indicated that the external optical feedback operation could lead to several dynamical regimes [15–17], whose presence depends on the external cavity length and feedback strength. In particular, it is known that chaotic oscillations, named coherence collapse, can highly destabilize the laser performance [18, 19]. In practical optical fiber communication system, the maximum reflection strength from optical connectors is estimated as large as 13% [20]; a criteria from IEEE 802.3ah suggests the reflection tolerance of an optical interconnect should be higher than -26 dB [21]. In this context, developing reflection-resistant optical transmitters becomes significant to overcome the issues from chip-scale back reflections, since on-chip optical isolators of poor-performance and high-cost are no longer obligatory. Our previous work has already discussed the optical feedback dynamics of silicon QD lasers in the long-cavity

* bozhang.dong@telecom-paris.fr

[†] frederic.grillot@telecom-paris.fr

regime (LCR) [14, 19], in which a high degree of stability of such lasers was revealed without any chaotic oscillations. In addition, compared to QD lasers operating on the excited state (ES), those operating on sole ground state (GS) are also better candidates for isolator-free PIC applications, owing to their stronger damping of the relaxation oscillations [19, 22]. However, to understand what really happens on the scale of a PIC, an in-depth investigation of the optical feedback dynamics from long to short-cavity regimes (SCR) is necessary to reach a comprehensive analysis of the reflection sensitivity of silicon QD lasers. In practical case, the intra-chip and inter-chip scale is in the order of micrometers and centimeters, respectively [23].

This work reports on the dynamics of a $1.3 \mu\text{m}$ epitaxial InAs/GaAs QD Fabry-Perot (FP) laser on silicon operating under various feedback conditions. In particular, by analyzing the full transition from SCR to LCR, our results confirm that the QD device still exhibits a very strong resistance to external optical feedback without showing any chaotic oscillations even at the maximum feedback strength of $\sim 70\%$ (-1.55 dB). Such remarkable features are attributed to the material properties of the QDs, leading to a small linewidth enhancement factor [24, 25], a strong damping [7] and sole GS lasing [22]. Nevertheless, by tightly controlling the feedback parameters from SCR to LCR, various dynamical states such as regular pulse package (RPP), period-one (P1), quasi period-one (Q1) and quasi-periodic (QP) oscillations are identified. Our previous work in LCR demonstrated that the feedback insensitivity of QD laser was improved by applying p-type doping in the active region [10]. In this work, we investigate the p-doping effect on the feedback sensitivity of silicon QD lasers in full transition from SCR to LCR. To do so, another device grown with the same QDs, but without p-modulation doping in the active region is used for comparison. **However, note that the facet reflectivities of the p-doped laser are left as-cleaved, which are much lower than those of the undoped device.** On both devices, the tolerance for optical feedback is much enhanced by shortening the external cavity length from LCR to SCR. In other words, they exhibit strong resistance to inter-chip scale back reflection in absence of any unstable oscillations. Moreover, these results turn out that the reflection resistance of device can be further improved on the intra-chip scale. In agreement with the results reported in [10], the p-doped device generally shows a higher degree of stability despite it is much more open to the external world with as-cleaved facets. As opposed to that, the undoped laser has much larger power reflectivities on both facets, which means that in this case the light from the external cavity is not strongly coupled with the QD active medium. Therefore, the better performance of the p-doped device is purely attributed to the p-doping. The present study brings now a detailed understanding of the nonlinear dynamics of multimode QD lasers on silicon, which gives insights for developing ultra-stable silicon transmitters

for isolator-free PIC applications.

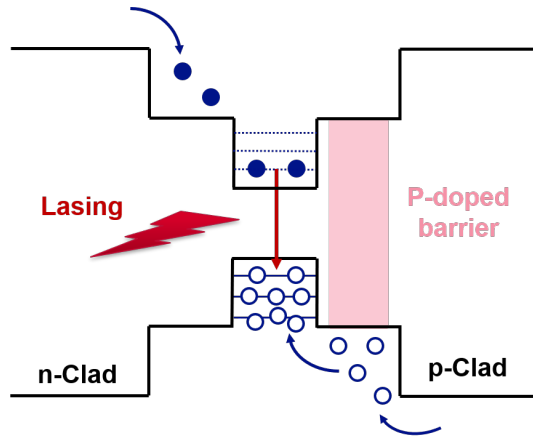


FIG. 1. Schematic illustration of the radiation process in a dot-in-a-well heterostructure with p-doped barrier.

II. EXPERIMENTAL CONFIGURATION

In the QD active region, the valence states are relatively less confined than the highly separated conduction band states, due to the heavier effective mass of holes. In this case, the rapid hole thermalization becomes one of the main mechanisms causing the gain to be temperature sensitive. Consequently, when QDs are undoped, the total charge density in the active layer increases in order to obtain a sufficient hole population in the QD ground state. However, in order to achieve a population inversion, the charge neutrality must also increase the total number of electrons hence leading to a higher radiative current along with a reduced differential gain. Although p-doping was already used in QW devices to mitigate the problem of closely spaced hole subbands, it can also be applied to QD lasers to overcome the broadening of hole population and optimize the performance of QDs in terms of thermal stability. Figure 1 schematically illustrates the optically induced carrier transitions and energy levels in a layer of p-doped dot-in-a-well heterostructure. As injected electrons have a high probability of residing only in the QD GS, the large concentration of holes ensures that the injected electrons always find GS holes with which to recombine. Let us stress that the n-doped active region does not offer similar advantages either to increase the differential gain or the thermal stability. Indeed, once the electron state is full, the increase in gain is limited because it comes from the sole injection of holes into the GS holes which is a very slow process whereby holes are thermally distributed over a number of levels. Recent studies reveal that the p-doping technique is beneficial for reducing the carrier density required to achieve a certain quasi Fermi-level separation, hence resulting in the improvement of modal gain and differential gain. It also decreases the linewidth enhancement factor which

is of first importance to improve high temperature lasing characteristics, reliability of QD lasers on silicon as well as intensity noise properties [10, 26]. Moreover, the p-doped QD lasers are touted for their better resistance against optical feedback with a critical feedback level beyond that of the undoped case [10]. This last feature is mostly attributed to the reduction of the linewidth enhancement factor in presence of p-doping. It may also be explained by the slight increase of the Shockley-Read-Hall (SRH) recombination rate especially at a high p-doping concentration ($\geq 10^{18} \text{cm}^{-3}$), the latter is directly linked to the laser's damping factor hence the feedback sensitivity [27]. Hereinafter, we confirm the importance of p-doping on the optical feedback performance of QD lasers on silicon.

In this study, both the QD devices presented in the following experiments are designed for emission on GS at 1310 nm at room temperature and their epitaxial structure based on the typical design is depicted in Fig.2. The active region consists of five periods of InAs QDs embedded in $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ QWs. The QD density is $6.5 \times 10^{10} \text{cm}^{-2}$ with photoluminescence (PL) full-width at half maximum below 30 meV. In the p-doped device, each dot layer is separated by a 37.5 nm GaAs spacer, in which a 10 nm-thick $5 \times 10^{17} \text{cm}^{-3}$ p-type material layer is added to optimize the laser performance including the improvement of modal gain and thermal stability [26]; whereas for the undoped one, the p-doping is absent. The whole structure of active region is then directly grown on an on-axis (001) GaP/silicon wafer in a Veeco Gen-II molecular beam epitaxy chamber. Further details of the epitaxial growth are available elsewhere [9].

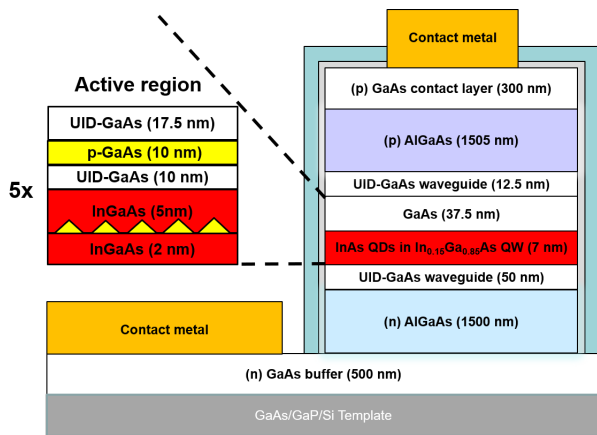


FIG. 2. Schematic illustration of the laser epitaxial structure; the close-up on the left depicts one period of the active region of the p-doped QD laser.

The p-doped QD laser is fabricated with standard dry etch and electron beam metal deposition techniques. Its FP cavity is 1.35 mm long, with $3.5 \mu\text{m}$ wide ridges deeply etched through the active region, and two top metal contacts are used for electrical injection. In order to improve the feedback strength in the following exper-

iments, both facets of this laser are left as-cleaved with reflectivities of 32%. In comparison with the p-doped laser, another device grown from the same techniques except for the active region being undoped is investigated. To optimize the lasing efficiency, its front and rear facets of are applied by $\text{SiO}_2/\text{Ta}_2\text{O}_5$ coatings to give reflectivities of 60% and 99%, respectively. Other structure details can be found in [7, 10]. In this study, the p-doped laser exhibits strong resistance to optical feedback without showing any unstable oscillation at room temperature (20°C), in this case the experiments based on this device described hereinafter are performed at 30°C where the destabilization takes place. On the other hand, experiments on the undoped laser are effected at 20°C . In this study, we do not investigate the optical feedback operation on those devices at a higher temperature, given that the undoped QD laser exhibits a poor thermal stability due to the aforementioned rapid hole thermalization, whose presence limits its operation at a higher temperature. In particular, the output power is too much limited for conducting experiments over 30°C . A previous study also demonstrated that an undoped QD laser suffers from both intensity and wavelength fluctuations under optical feedback at 30°C [10]. Figure 3(a) depicts the multimode optical spectrum of the p-doped QD laser at 160 mA, such a condition is marked by the red bullet on the light-current curve measured at 30°C shown in the inset. As shown, the p-doped laser with threshold current I_{th} of 36 mA exhibits a sufficient output power over 15 mW. In order to avoid power roll-over, the bias current in the following experiments is fixed at 125 mA ($3.4 \times I_{th}$) and 160 mA ($4.4 \times I_{th}$) to maximize the output power. It is worth noting here that the emission on ES does not take place up to $5 \times I_{th}$, such a large ES-to-GS lasing threshold ratio is also beneficial for strengthening the resistance against external optical feedback for QD lasers [19]. For comparison, a similar bias-to-threshold ratios as the p-doped device are kept for the whole investigation of the undoped laser dynamics.

Figure 3(b) depicts the free-space optical feedback setup for the p-doped QD laser. The device is mounted on a suspended optical table to minimize the environmental perturbations. Owing to the symmetric as-cleaved coating design of this laser, the setup is thus separated into two parts: one part at the side of front facet is for optical feedback operation and the other at the side of rear facet is for light detection and analysis. The free-space external cavity was located outside of the front facet of laser, in which the lasing emission is firstly collimated and then reflected by a movable mirror mounted on an optical rail. The latter allows us to adjust the external cavity length L_{ext} from 4 cm (minimum, blue) up to 50 cm (maximum, red). In a technical view, reducing the L_{ext} to a few centimeters is complicated in free-space operation, hence well arranging the experimental apparatuses is necessary. In this study, the SCR and LCR is defined as the ratio of f_{RO}/f_{ext} being <1 or >1 , respectively [28], with f_{RO} the relaxation oscillation frequency

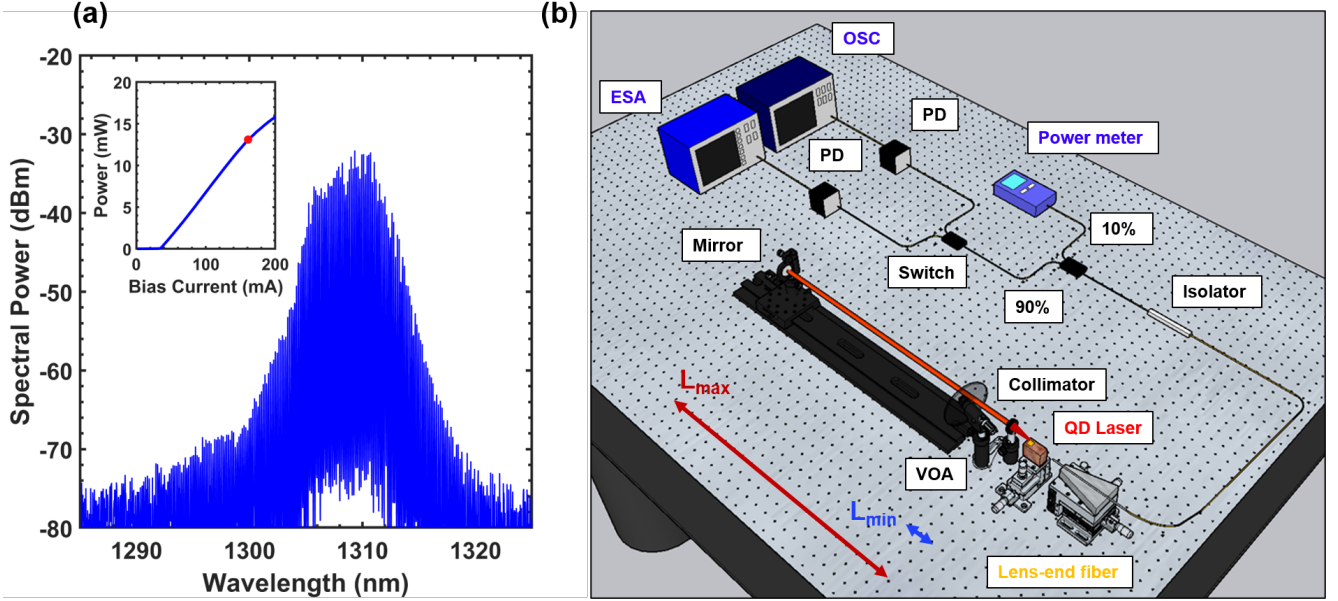


FIG. 3. (a) Optical spectrum on of the p-doped laser at 160 mA ($4.4 \times I_{th}$, red marker). The inset depicts the light-current characteristics measured at 30°C . (b) Schematic of the experimental setup for measurement of the QD lasers. VOA, variable optical attenuator; PD, 12 GHz photodiode; ESA, electrical spectrum analyzer; OSC, oscilloscope.

of the solitary laser and $f_{ext} = c/2L_{ext}$ the frequency of the external cavity. Thus for the p-doped laser, f_{RO} being 2 GHz and 1.5 GHz at 160 mA and 125 mA, respectively, ensure the corresponding ratio of f_{RO}/f_{ext} ranging from 0.5 to 7 and from 0.4 to 5, which finely probes the laser dynamics in transition from SCR to LCR. For each measurements at different L_{ext} , the focus of the collimator needs to be readjusted in order to precisely send the coupled light onto the mirror. In this configuration, the feedback strength r_{ext} being defined as the ratio of the returning power to the laser output power is controlled by a free-space variable optical attenuator (VOA), which gives extra loss in the external cavity thus allows us to slightly modify the r_{ext} . On this setup, the r_{ext} taking into account the coupling loss between the facet and the external cavity ranges from 0.04% (-34 dB) to $\sim 70\%$ (-1.55 dB), with an accuracy better than 0.01%. On the light detection path, laser emission from the rear facet is firstly coupled by an AR coated lens-end fiber and isolated to avoid any back reflection from the setup. The coupled light is then sent to an electrical spectrum analyzer (ESA) and an oscilloscope (OSC) for further analysis. The experimental setup for the undoped device only emitting from front facet is a little different from that for the p-doped one. In this case, a 50/50 free-space beam splitter (BS) is placed outside of the collimator in order to divert 50% output light into the detection path (setup not shown in this paper). As such, the maximum r_{ext} in the external cavity taking into account the loss from the BS is limited to $\sim 22\%$. Adjusting the L_{ext} ranging from 4 cm to 50 cm, corresponding f_{RO}/f_{ext} of the undoped laser therefore ranges from 0.8 to 10, where its f_{RO} is 3

GHz at $3 \times I_{th}$. Further details of this experimental setup can be found in [29].

III. RESULTS AND DISCUSSIONS

Results displayed in this section are mainly taken from the p-doped QD laser. Extending the L_{ext} from SCR to LCR, different self-pulsation dynamics of the device are identified. Figure 4(a) depict the radio-frequency (RF) spectrum (left column), time series (middle column) and phase portraits (right column) of the device operating at 160 mA with $r_{ext}=68.2\%$ (-1.66 dB) and L_{ext} being 4 cm ($f_{ext}=3.75$ GHz). Corresponding ratio of f_{RO}/f_{ext} being 0.5 indicates that the f_{ext} was largely beyond the f_{RO} of the QD laser, where the RPP takes place. As shown in Fig.4(a-ii), a series of regular pulses oscillating at f_{ext} are modulated by a slower envelope, whose repetition frequency f_{RPP} being 55 MHz is clearly depicted in the inset of Fig.4(a-i). On the other hand, the inset of Fig.4(a-ii) highlights the fast oscillations at f_{ext} within one envelop. It is worth noting here that such a large ratio of f_{ext}/f_{RPP} being 68 is much more than those observed on other devices including QW and QD lasers [28, 30, 31]. Moreover, the phase portraits shown in Fig.4(a-iii) reveals that the slow oscillation frequency coincident with f_{RPP} does not bring huge discrepancy from the single-frequency pulsations since only one cycle can be identified, however, the laser system suffers from strong instabilities induced by the feedback phase. Note that the slow oscillations at the border of RPP regime exhibits sustained instability on temporal scale, whose

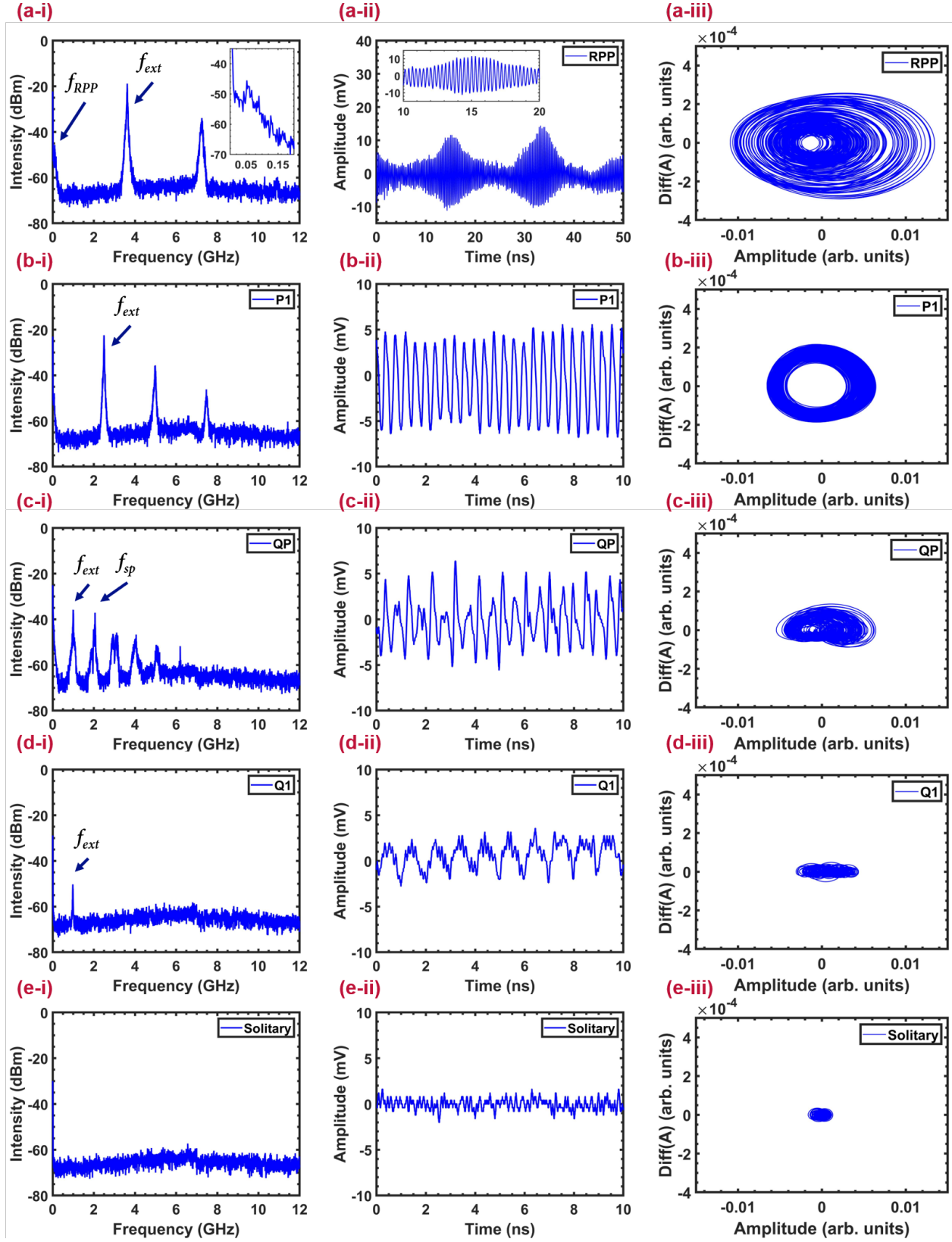


FIG. 4. Electrical spectra (left), time series (middle), and phase portraits (right) of the p-doped QD laser with $(r_{ext}, L_{ext}) =$ (a) (68.2%, 4 cm), (b) (68.2%, 6.5 cm), (c) (68.2%, 15 cm), (d) (33%, 15 cm), and (e) solitary, when it was biased to 160 mA. f_{ext} , frequency of the external cavity; f_{sp} , self-pulsation frequency.

presence performs a variable f_{RPP} as the time changes. To overcome this issue, it would be important to further reduce the external cavity to fully probe the pure RPP regime from which the laser output can resemble to that of a mode-locked laser. Extending the L_{ext} to 6.5 cm while ensuring the same $r_{ext}=68.2\%$, the device enters into P1 state, corresponding RF spectrum, time series and phase portraits are shown in Fig.4(b). In this case, the ratio of f_{RO}/f_{ext} being ~ 0.9 indicates that the QD laser still operates in SCR. At this stage, the regular pulses oscillating at $f_{ext}=2.3$ GHz are shown in Fig.4(b-ii), the higher harmonics of f_{ext} are identified in Fig.4(b-i). Compared to the phase portraits of RPP, those of P1 shown in Fig.4(b-iii) reflect the uniformity of the single-frequency oscillations by exhibiting a pretty regular cycle. Further increasing the ratio of f_{RO}/f_{ext} to ~ 2 by extending the L_{ext} to 15 cm, the device therefore operates in LCR. Still ensuring the maximum $r_{ext}=68.2\%$, both the f_{ext} and the self-pulsation frequency f_{sp} shown in Fig.4(c-i) contribute to shape the waveform (Fig.4(c-ii)) thus lead the device into the QP state. When the L_{ext} is shorter than the coherence length L_{coh} of laser, the f_{sp} is coincident with the higher harmonics of f_{ext} thus exhibit strong dependence of L_{ext} . Corresponding discussions will be performed in this paper later on. On the other hand, the f_{sp} is observed to fluctuate around f_{RO} as the L_{ext} changes. The difference between QP and P1 can be clearly seen from the phase portraits (Fig.4(c-iii)) through the exhibited two cycles, which is the sign of two-frequency oscillations. In LCR, it is worth stressing that the f_{sp} should coincide with the f_{RO} in free running operation. Nevertheless, our following results demonstrate that the f_{sp} varies with the change in L_{ext} , whose presence depends on the mode competition between the linear modes near the f_{RO} [32]. The influence of L_{ext} on f_{sp} can be eliminated once the L_{ext} exceeds the coherence length. In the case of QD lasers with typically narrow RF linewidth below 200 kHz [33, 34], their coherence length is about several hundred meters [22, 35]. In this study, the r_{ext} effect on laser dynamics is also investigated. To do so, the r_{ext} is decreased to 33% (-4.8 dB) while fixing the $L_{ext} = 15$ cm, the device becomes more stable and entered into Q1 state. Different from the P1 state described in prior studies [36, 37] and that aforementioned in this section, the oscillation frequency coincident with f_{ext} (Fig.4(d-i)) does not show any higher harmonic. Note that the RF intensity of the f_{ext} is quite low thus the waveform shown in Fig.4(d-ii) is largely influenced by the high frequency noise, whose presence makes the corresponding phase portraits (Fig.4(d-iii)) hardly to be distinguished from those at the solitary state (without feedback). To be reference, the spectra of the solitary state are shown in Fig.4(e).

In this study, it is worth noting that the QD laser does not exhibit any chaotic oscillations from SCR to LCR, even if it operates under strong optical feedback with $r_{ext} \simeq 70\%$. Prior studies revealed that the QW lasers suffered from strong instabilities against optical

feedback, performed by generally exhibiting chaotic oscillations with r_{ext} below 5% in both SCR and LCR [13, 32]. Those features definitely limited their applications for isolator-free integration. In this context, the chaos-free QD laser reported in this paper is important to be applied in PICs to improve their robustness against chip-scale back reflections. It is worth stressing that the remarkable feedback resistance of the device studied are attributed to some peculiar properties of QDs. Compared to QW lasers, our previous work performed in LCR has demonstrated that the enhanced feedback insensitivity of silicon based QD devices originated from the large damping rate over 30 GHz [7] and the near-zero linewidth enhancement factor [24, 38]; in addition, the p-type doping in the active region is also beneficial for further improving the tolerance to external optical feedback, corresponding discussions are available in the end of this paper. On the other hand, the aforementioned periodic oscillations in the p-doped laser subject to optical feedback exhibit strong dependence on the L_{ext} , which are also studied in this work.

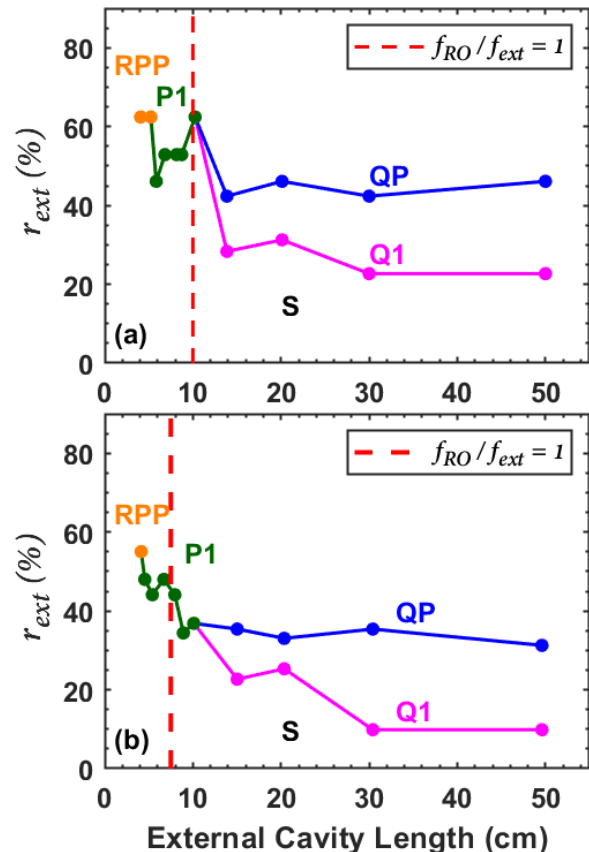


FIG. 5. Mappings of the dynamical states of the p-doped QD laser under different feedback conditions at (a) 125 mA and at (b) 160 mA. The vertical red dashed lines depict the boundaries of the SCR and the LCR.

By increasing the r_{ext} from 0.04% to $\sim 70\%$, one can extract the boundaries associated with the different pe-

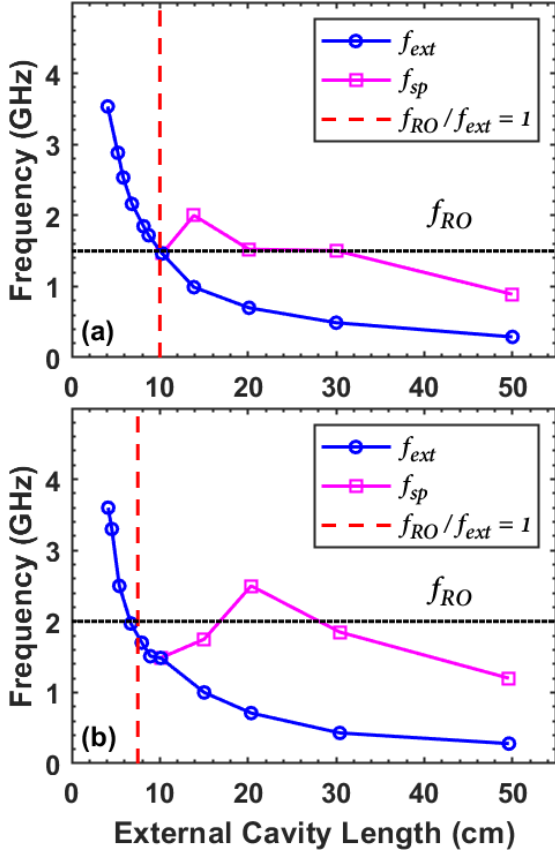


FIG. 6. The oscillation frequency f_{FO} (blue circle) and f_{SO} (magenta square) as a function of L_{ext} of the p-doped QD laser at (a) 125 mA and at (b) 160 mA, the horizontal dotted black lines illustrate the free-running f_{RO} . The vertical dashed red lines depict the boundaries of the SCR and the LCR.

periodic states both in SCR and LCR. To do so, the onset of each periodic oscillation is defined as the corresponding excited oscillation frequency being 5 dB above the free-running noise level. Figure 5(a) and (b) depict the aforementioned boundaries as a function of the L_{ext} , when the device operates at 125 mA ($3.4 \times I_{th}$) and 160 mA ($4.4 \times I_{th}$), respectively. The vertical dashed red lines corresponding to the condition $f_{RO}/f_{ext} = 1$ are performed to separate the SCR and LCR. In order to improve the precision, measurements are performed by varying the L_{ext} every centimeter in SCR while larger steps are taken in LCR. Our results demonstrate that the device becomes more stable against optical feedback at a lower bias current where the region of the steady state (S, marked in black) expands and r_{ext} required for the laser to excite instability increases. This feature is attributed to the reduced linewidth enhancement factor above threshold [10]. In both cases, the boundaries associated with unstable oscillations exhibit strong undulations in SCR, whose presences are attributed to the coupling degree between the internal and external cavity modes [39]. On the other hand, the QD laser

is less stabilized with a small fraction of optical feedback in LCR, thus the instability boundaries progressively become rather independent of the L_{ext} . Operating in SCR, our results demonstrate that the RPP oscillations (marked in orange) only take place in the ultra-short delay region where $f_{RO}/f_{ext} < 0.5$, since the influence of the feedback phase is much enhanced in this regime [28]. Extending the L_{ext} to $f_{RO}/f_{ext} \simeq 1$, the device only exhibits P1 oscillations (marked in green). It is worth stressing that the QD laser remains in the S region with r_{ext} below 35% in SCR. More dynamical states are identified in LCR. Increasing the r_{ext} , the device remains in the S region under weak r_{ext} , until it oscillates at f_{ext} thus enters into Q1 state (marked in magenta), then the f_{RO} is excited performing the onset of QP oscillations (marked in blue).

In order to understand the periodic stability enhancements taking place in the condition satisfying $L_{ext} = mc/2f_{RO}$ ($f_{RO}/f_{ext} = m$, m is integer), Fig.6(a) and (b) display the excited f_{sp} as a function of the L_{ext} at 125 mA ($3.4 \times I_{th}$) and 160 mA ($4.4 \times I_{th}$), respectively. The vertical dashed red lines corresponding to $f_{RO}/f_{ext} = 1$ is once again indicating the separation of regimes. In agreement with prior studies, the f_{sp} coincides with the f_{ext} (marked in blue circle) in SCR [40], whereas it oscillates at both f_{ext} (marked in magenta square) and $\sim f_{RO}$ (marked in blue circle) in LCR. It is worth stressing that the strong mode competition taking place in f_{RO}/f_{ext} being an integer is indeed beneficial for enhancing the feedback insensitivity by improving the $r_{ext,p}$ shown in Fig. 5(a) and (b) [39]. Nevertheless, the extension of the L_{ext} within one period is found to not only largely degrade the laser stability against optical feedback (lower $r_{ext,p}$) but also decrease the f_{FO} . These features are attributed to the decrease of damping factor with increasing the L_{ext} [41]. In addition, the undulations of both the f_{sp} and the r_{ext} associated with the onset of unstable oscillations in LCR reveal that the QD laser still operates in the coherent feedback regime, in which the laser dynamics is largely influenced by the feedback phase. This coherence would be eliminated once further increasing the ratio of f_{RO}/f_{ext} until the f_{FO} coincident with free-running f_{RO} becomes independent of the L_{ext} .

Prior studies on p-type doping in QD lasers revealed that it was beneficial for enhancing the laser performance including higher material gain [9], larger modulation bandwidth [42] and better thermal stability [10]. Our previous work also demonstrated that the feedback insensitivity of QD laser in LCR could be improved by applying this technique [10]. In this work, we go an important step beyond by investigating the p-doping effect on the feedback sensitivity in SCR, where the feedback conditions closely resemble those of PICs. Figure 7 depicts the onset to periodic oscillations $r_{ext,p}$ as a function of L_{ext} for the p-doped (blue square) and undoped (red circle) QD laser at $\sim 3 \times I_{th}$, corresponding boundaries of SCR and LCR are marked by dashed or dotted lines in same colors. As aforementioned, the operation tem-

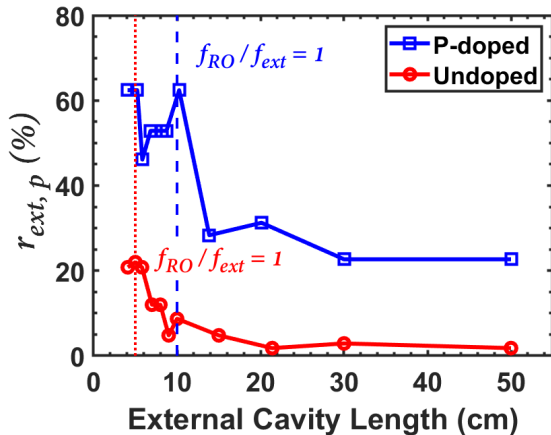


FIG. 7. The onset of periodic oscillations $r_{ext,p}$ associated with L_{ext} of the p-doped (blue square) and undoped (red circle) QD laser. Both devices was biased at $\sim 3 \times I_{th}$. The vertical dashed blue and dotted red lines depict the boundaries of the SCR and the LCR of the p-doped and the undoped device, respectively.

perature of the p-doped and undoped device is $30^\circ C$ and $20^\circ C$, respectively. It is worth stressing that both the as-cleaved facets of the p-doped device make it more open to the external world than the undoped one, which is not always favorable for maintaining the tolerance to optical feedback [14]. Nevertheless, the p-doped laser clearly displays a much stronger resistance to optical feedback than its counterpart even at a higher operation temperature hence exhibiting a higher $r_{ext,p}$ in full transition from SCR to LCR [10]. This remarkable performance improvement is mainly attributed to the reduced linewidth enhancement factor owing to the p-doping [10]. Importantly, both QD lasers studied exhibit remarkable tolerance for inter-chip scale back reflection. The improvement of feedback resistance with decreasing L_{ext} shows that these devices can be still reflection-resistant on the intra-chip scale. Furthermore, although the p-doped QD laser has a higher threshold current [9] and a lower damping rate [10], its stronger stability against back reflection fits very well the needs for high performance PICs oper-

ating without optical isolator.

IV. CONCLUSIONS

This work brings fundamental insight on the multi-mode optical feedback dynamics of InAs/GaAs QD lasers epitaxially grown on silicon. In agreement with prior studies, our results demonstrate that the silicon QD laser displays a strong resistance to optical perturbations without showing any chaotic pulsations whatever the external cavity length and feedback strength was. Such a remarkable feature is attributed to the very large damping factor, the near-zero linewidth enhancement factor and the participation of p-doping in the active region, which prevent it from any chaotic oscillations even within extreme feedback conditions. In this study, the evolution of the extracted boundaries associated with different dynamical states and the excited periodic frequencies unveil a clear dependence on the L_{ext} in SCR, while the system becomes rather independent of the feedback phase in LCR. Compared to the reflection-sensitive QW lasers, it is worth stressing that the observed strong tolerance for optical feedback in SCR is much beyond the IEEE 802.3ah standard, hence this study highlights the potential of epitaxial QD lasers on silicon as ultra-stable light sources applying on the scale of PICs. As a conclusion, these results provide useful guidelines for developing QD laser based PICs without the need of optical isolators, which is an important solution for realizing low-cost and energy-efficient data centers and supercomputer applications. The analysis of the pulsing states is also strongly driven by the growing interest in microwave photonic technology from which exciting perspectives can be envisioned such as the fabrication of an integrated device in a PIC capable of delivering microwave signals without the need of electrical modulation.

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