PHOTONICS Research

Multi-wavelength injection locked semiconductor comb laser

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Quantum dot lasers on silicon have gained significant interest over the past decade due to their great potential as an on-chip silicon photonic light source. Here, we demonstrate multi-wavelength injection locking of InAs/GaAs quantum dot Fabry–Perot (FP) lasers both on GaAs and silicon substrates by optical self-injection via an external cavity. The number of locked laser modes can be adjusted from a single peak to multiple peaks by tuning wavelength dependent phase and mode spacing of back-injected light through a Lyot filter. The multi-wavelength injection locked laser modes exhibit average optical linewidth of ~20 kHz, which are narrowed by approximately three orders of magnitude from their free-running condition. Furthermore, multi-wavelength self-injection locking via an external cavity exhibits flat-top optical spectral properties with approximately 30 stably locked channels under stable operation over time, where the frequency detuning is less than 700 MHz within 40 min. Particularly, FP lasers by direct epitaxial growth on silicon substrates are self-injection locked as a flat-top comb source with tunable free spectral range from approximately 25 to 700 GHz. The reported results emphasize the great potential of multi-wavelength injection locked lasers as tunable on-chip multi-wavelength light sources.

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1. INTRODUCTION

Optical frequency combs (OFCs) have large bandwidth and massive wavelength channels, making them a promising candidate for terabit/s wavelength division multiplexing (WDM) transmission [1–4] and microwave photonics applications [5]. Micro-ring-resonator (MRR)-based Kerr soliton combs have been extensively explored over the past few years, which provide outstanding properties, such as narrow linewidth, ultra-broad bandwidth, and high conversion efficiency [6–8]. In the case of WDM communications, recently, there has been a strong surge of spectral flat-top comb lasers, which has also brought significant attention to active optical comb sources such as semiconductor mode locked lasers (MLLs) [3,4,9]. For the Si photonic integration perspective, MLLs on a Si substrate via either bonding method or epitaxial growth appear to be the technical trend to achieve on-chip compact comb sources [10–17]. Furthermore, in order to achieve laser sources with great tunability and narrow linewidth, self-injection locked lasers based on a high-Q external cavity are regularly incorporated [18]. Recently, semiconductor lasers with ultra-narrow linewidth have been demonstrated by self-injection locking via an ultra-high-Q Si nitride ring resonator [19–24], which could be a holy grail of achieving compact narrow-linewidth comb lasers. In general, external cavity injection locked lasers are implemented on distributed feedback (DFB) lasers, which could only achieve single wavelength injection locking. With the multi-wavelength Fabry–Perot (FP) laser diode, which is an inexpensive solution, injection locking of multiple frequencies appears to be a great challenge. The ideal concept is to injection lock multi-wavelength FP lasers by including external cavity filters, which would provide wide tunability, narrow optical linewidth, and flat-top multi-wavelength comb lasers.

In this work, we demonstrate multi-peak injection locking of an InAs/GaAs quantum dot (QD) FP laser directly grown on both GaAs and Si (001) substrates with buried (111)-faceted Si sawtooth structures [13]. To note, QD lasers on GaAs and Si substrates behave differently during the multi-wavelength injection locking scheme, which will be discussed in detail in the main context. By self-injection locking through an external fiber cavity with a Lyot filter, multiple modes of the FP laser are individually injection locked with narrowed optical linewidth of approximately 20 kHz for all selected modes. The injection locked mode spacing in the GaAs-based comb is discretely adjustable from 75 to 750 GHz by tuning the birefringence of the Lyot filter [25]. For the Si-based comb laser, the injection locked comb lines exhibit enhanced flat-top spectra with 10 dB bandwidth of 13 nm, while its comb spacing can be tuned from 25 GHz towards 700 GHz. Compared with electro-optic (EO) modulation generated OFCs, the injection locked OFC is capable of achieving larger free spectral range (FSR) and narrowed optical linewidth. Furthermore, different from the large energy variation in single comb lines with a $sech^2$-shaped soliton comb generated in MRRs, the advance of relatively small power variation among comb channels makes injection locked combs desirable for WDM applications [26].

2. DEVICE DESIGN AND EXPERIMENTAL ARRANGEMENTS

Conventional two-section MLLs with saturable absorbers are strongly dependent on amplitude modulation (AM) to modify/shape comb spectra. In contrast, frequency modulation (FM) is usually observed in fast gain media, e.g., QD lasers and quantum cascade lasers (QCLs) [27–29]. Fast gain dynamics normally lead to spatial hole burning and phase modulation [30–32], which can effectively trigger phase locked comb generation. Although both AM and FM locking techniques have their own repetition rates, AM locked lasers produce narrow pulses, while FM locked lasers generate quasi-continuous signals. The single-section QD FP laser is normally considered as an FM locked comb laser [33]. But, the drawback of implementing a QD FP laser diode as a comb laser source is that the mode spacing or so-named repetition rate regularly depends on the cavity length, which has no accessibility to mode spacing tuning once the device dimension is determined. Thus, the comb spacing of semiconductor MLLs is regularly limited within 100 GHz [4,34,35]. Therefore, to achieve a flat-top comb source with tunable comb spacing and narrow optical linewidth, an external cavity with wavelength dependent phase tuning ability and mode filtering is desired.

Here, we have examined two different types of InAs QD FP laser diodes epitaxially grown on GaAs and Si substrates, where the individual device structures are shown in Figs. 1(b) and 1(c). The FP laser chips are mounted on a thermoelectric cooler at room temperature to achieve stable comb operation for subsequent self-injection locking. The QD FP lasers on both a standard GaAs substrate (chip 1) and a Si substrate (chip 2) are separately butt-coupled into a lensed fiber followed by a polarization-maintained fiber (PMF)-based Lyot filter

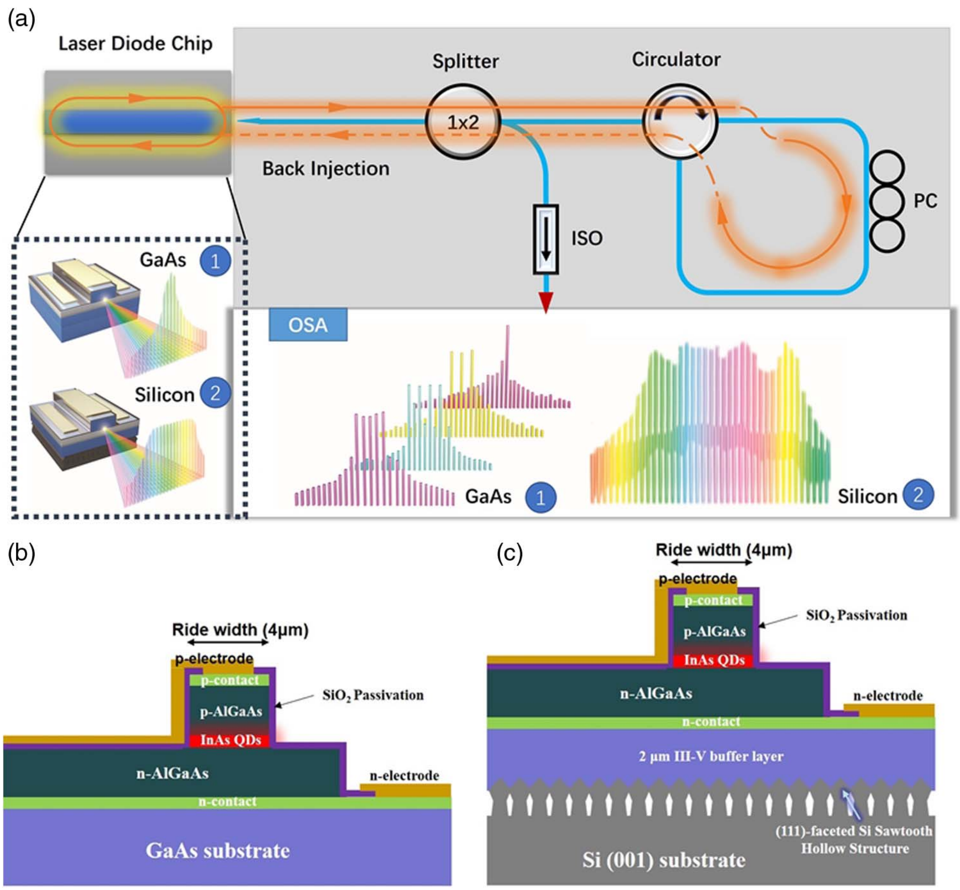

Fig. 1. (a) Schematics of two types of lasers (InAs QD laser on GaAs/chirped InAs QD laser on Si) self-injection locked into multiple wavelengths via a PM-fiber-based external cavity. (b) Structure layout of InAs QD laser grown on standard GaAs substrate. (c) Structure layout of chirped InAs QD laser epitaxially grown on Si (001) substrate.

[36–40], and then directly fed back to the laser itself, as shown in Fig. 1(a). Here, the Lyot filter consists of a PMF with fixed length, PMF circulator, and polarization controller (PC), where it has one half-wave plate sandwiched by two quarter-wave plates, which together provide an arbitrary phase shift from 0 to 2π.

The QD laser on GaAs substrate (QDLGS) is a standard commercial QD laser structure that generates a Gaussian shape comb spectrum. The InAs QD laser directly grown on Si substrate (QDLSI) exhibits a broader and flatter optical spectrum, contributing to the strain induced chirped InAs QDs. By assistance of a Lyot filter, comb lines with tunable FSR are fed back into the original laser cavity for multi-wavelength injection locking.

3. MEASUREMENTS AND DISCUSSION

Starting with standard InAs QD laser on GaAs, the laser diode is directly coupled into the Lyot fiber filter, acting as an external cavity for self-injection locking. The initial launching power is approximately 1.5 mW at a central wavelength of 1302 nm. The original comb spectrum of QDLGS [Fig. 2(a)] has relatively large optical linewidth of approximately 16 MHz for individual comb lines, measured by the self-heterodyne linewidth measurement method.

By coupling the initial Gaussian shape comb spectrum [Fig. 2(a)] into a fiber loop, the comb spectrum is re-selected by the Lyot filter with mode spacing of 300 GHz, which is the fourth order of the original 75 GHz comb spacing. The FSR of Lyot filter is created by the phase shift $\Gamma(=2\pi BL/\lambda)$ between two orthogonal polarization modes of PMFs [36], where B and L are the Lyot filter birefringence and PMF length, respectively. The FSR can be successfully tuned by introducing additional phase shift between 0 to 2π, which is achievable via adjusting waveplates of the PC; that is, varying the birefringence of the Lyot filter. The filtered comb spectrum is then back-injected into the laser cavity with wavelength dependent phase tuning. As shown in Fig. 2(b), the initial 75 GHz comb is self-injection locked while converting into a 300 GHz comb. Most importantly, four self-injection locked comb lines now exhibit a flat-top spectrum instead of the previous Gaussian-shaped comb spectrum. Now, the power variation among all comb lines is

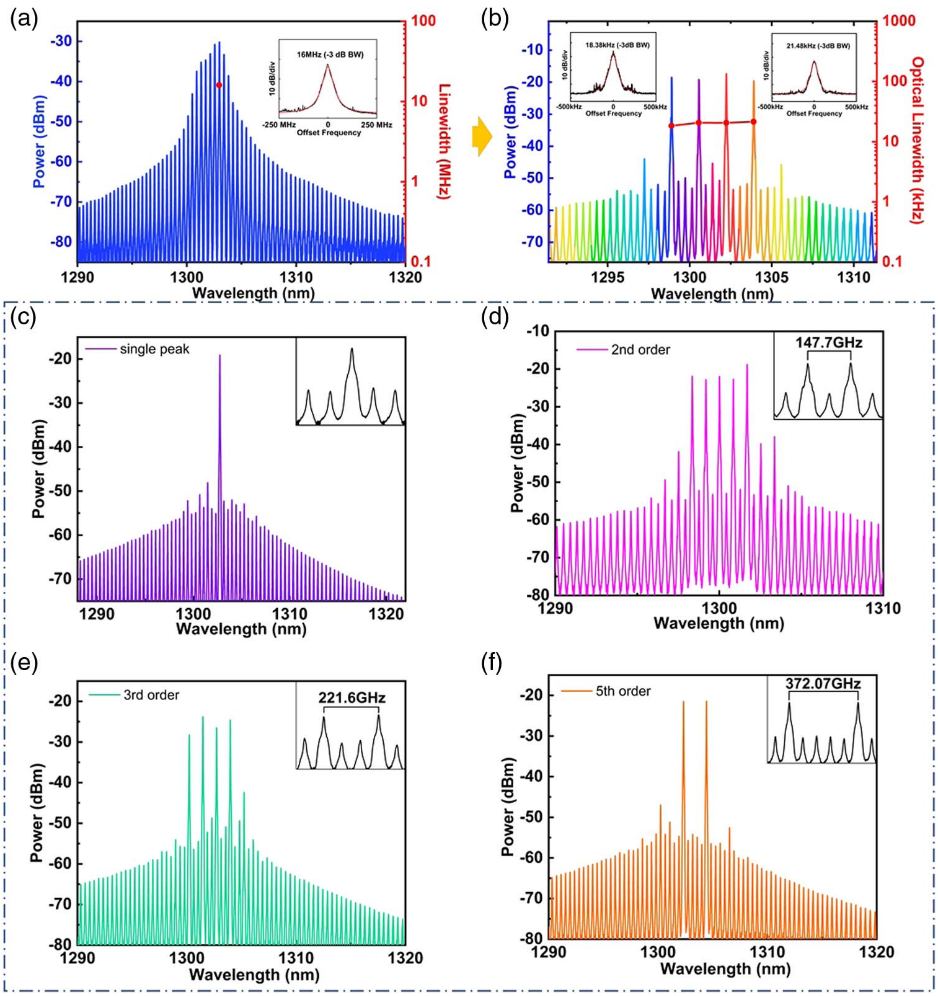

Fig. 2. (a) Optical comb spectrum of free-running InAs/GaAs QDLGS. Inset: measured single-channel optical linewidth. (b) Optical comb spectrum of self-injection locked InAs/GaAs QDLGS with narrowed optical linewidth. Insets: measured optical linewidth of self-injection locked comb lines. Optical spectra of (c) single peak injection locked, (d) second-order injection locked, (e) third-order injection locked, and (f) fifth-order injection locked lasers. Insets: zoom-in spectra of different orders of injection locked conditions, which match the y scale of the main panel.

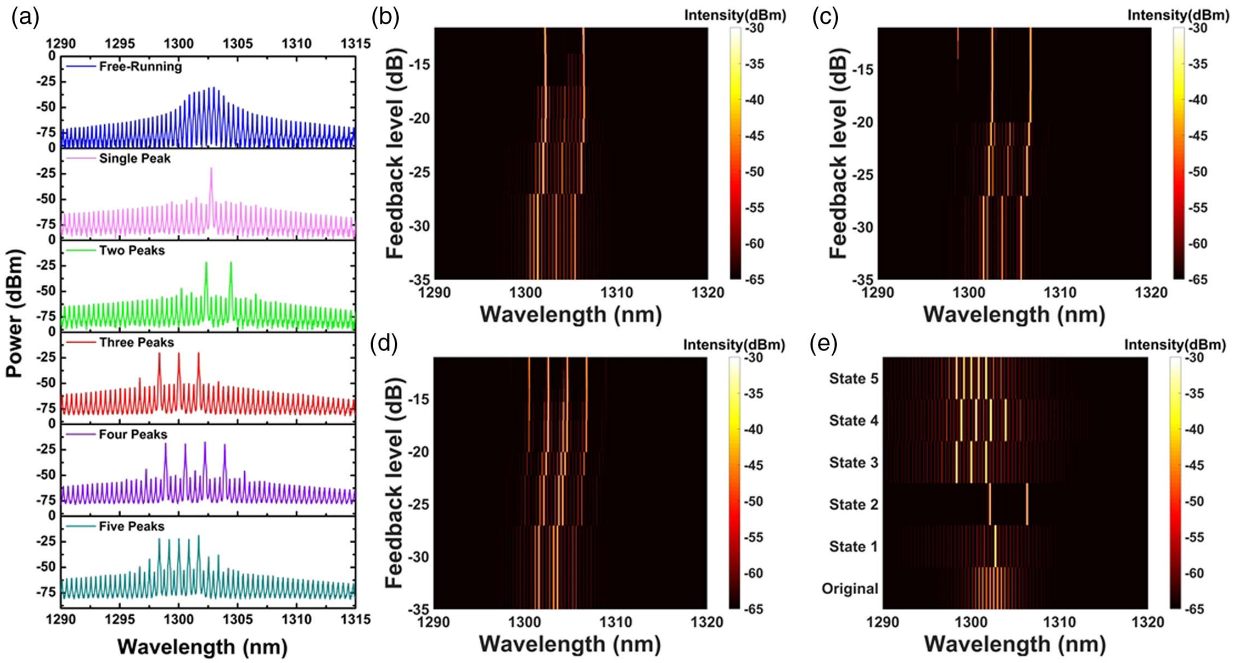

Fig. 3. (a) Optical comb spectral evolution of InAs/GaAs QDLGS from free-running condition into multi-peak injection locking states (single peak to five peaks). Spectral mapping of FP laser diode under different feedback levels (−35 dB to −10 dB) for (b) dual-peak injection locking state, (c) three-peak injection locking state, and (d) four-peak injection locking state. (e) Spectral mapping of multi-peak injection locking states.

smaller than 3 dB. All other sidemodes are strongly suppressed after multi-wavelength injection locking, as the injection locked comb lines are more strongly phase locked than other modes. The phase tunability here is triggered by a quarter-wave plate of an external PC, which will be explained in the later section. Moreover, in the inset of Fig. 2(b), the optical linewidths of four injection locked comb lines are simultaneously narrowed to an average value of approximately 20 kHz by almost three orders of magnitude from the original single sideband (SSB) comb line.

Here, the Lyot filter has been investigated as PMF loop mirror filter (PMF-LMF) [40]. By tuning the effective PMF length or PC, the variation of the birefringence B can lead to corresponding tunability of FSR. Here, the comb spacing and number of injection locked comb lines can be controlled by adjusting the angle between the TE mode and PM fiber, PM fiber length, polarization state of the PC, and feedback power level.

By selecting different comb spacing, we could achieve a multi-peak injection locked comb from second-order to tenth-order mode spacing. The optical spectra from the second order to fifth order are shown in Figs. 2(b)–2(e), where the higher-order spectra can be provided upon request. To note, the single peak injection locking condition [Fig. 2(c)] is achieved when the Lyot filter modulated FSR is broader than the entire laser bandwidth. Though, tunable comb spacing from 150 to 750 GHz can be realized in this experiment.

Beside the tunability of comb spacing, the number of comb channels can also be adjusted by varying the birefringence of the external cavity, as shown in Fig. 3(a). By tuning the waveplates of the PC, we could achieve from single peak injection locking towards five peaks injection locking continuously. It is difficult to achieve an additional number of peaks as they are basically out of the gain bandwidth of InAs QDs on GaAs. Furthermore, in order to measure the critical back-injection power required for multi-wavelength injection locking, a variable optical attenuator (VOA) is included inside the external cavity. Here, as shown in Figs. 3(b)–3(d), the FP laser diode requires approximately −15 dB feedback level to achieve the stable multi-wavelength injection locking condition for all different locking states. Multi-wavelength injection locked comb state mapping is displayed in Fig. 3(e).

Although a very wide comb spectrum could be achieved on QDLGS in Ref. [41], QDLGS normally exhibits limited gain bandwidth between 4 and 6 nm, so it is challenging to obtain multi-wavelength injection locked comb lines with more comb channels. Due to the broader size distribution of InAs QDs directly epitaxially grown on a GaAs/Si template, it provides a strained template to grow chirped QDs (leads to varied QD sizes) with enlarged gain bandwidth. In Fig. 4(a), a chirped InAs QD laser on Si initially operates in dual modes at a low injection current of 75 mA. Under an effective PMF length of 6 m [Fig. 1(a)], by carefully tuning the modal phase of back-injected light through the coupling distance or PC, we could achieve 10 self-injection locked modes at comb spacing of 75 GHz (third-order), as shown in Fig. 4(b). Note here, due to limited phase tuning precision of the PC, a single comb line at a wavelength of 1297 nm is more weakly injection locked than the others. The optical linewidths of each comb line is selected through an optical bandpass filter (OBPF) and measured by the self-heterodyne linewidth measurement method. The injected multi-peaks have optical linewidth ranging from 24 to 50 kHz from their original value of 14.6 MHz [Fig. 4(c)]. The intermodal suppression ratio is roughly between 25 and 30 dB in Fig. 4(b). As previously mentioned,

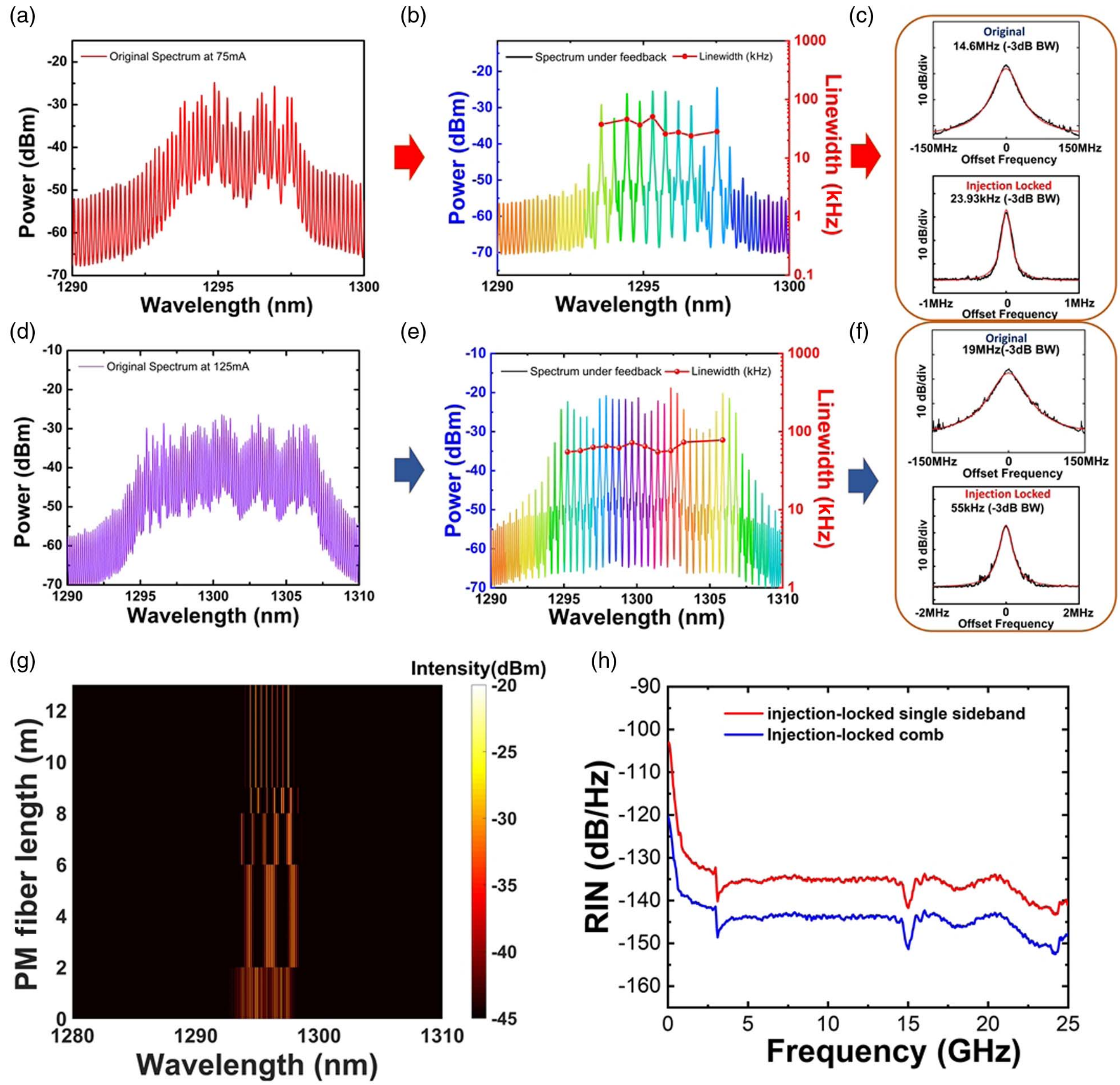

Fig. 4. Self-injection locking of chirped QDLSI. (a) Original optical spectrum of InAs QD laser on Si operated at injection current of 75 mA. (b) The multi-wavelength injection locked comb spectrum with 75 GHz comb spacing. Average optical linewidth of each comb line is approximately 20 kHz (red line). (c) The measured optical linewidth spectra of the original laser modes (top) and self-injection locked comb lines (bottom) via self-heterodyne method. The original optical linewidth of 14.6 MHz is narrowed to 23.93 kHz via the multi-wavelength injection locking technique. (d) The optical spectrum of InAs QD laser on Si operated at higher injection current of 125 mA with merged dual modes. (e) The multi-wavelength injection locked comb spectrum with 50 GHz comb spacing. Optical linewidth of each comb line ranges from 50 to 80 kHz (red line). (f) The measured optical linewidth spectra of original laser modes (top) and self-injection locked comb lines (bottom) both at driving current of 125 mA. The optical linewidths are 19 MHz and 53 kHz, respectively. (g) The optical spectral mapping against varied PMF loop length showing the relationship between FSR and effective PMF length. (h) RIN spectra of injection-locked comb source (blue) and injection-locked SSB up to 25 GHz.

the inhomogeneous nature of chirped InAs QDs on Si intends to introduce dual-mode operation, as indicated in Fig. 4(a). At an increased injection current of 125 mA, the dual modes intend to merge into a broader continuous spectrum, as shown in Fig. 4(d). Here, the filtered SSB of the free-running comb laser is measured with a linewidth of 19 MHz, which is relatively higher than the low-current operated InAs QD laser on Si due to carrier induced linewidth broadening. But, the number of injection locked comb lines is also increased to 30 peaks from 10 peaks at an operating current of 75 mA. The −10 dB bandwidth measured here is approximately 13 nm. Overall, with third-order injection locking, the Si-based laser is self-injection locked at 75 GHz mode spacing from their free-running FSR of 25 GHz at both 75 and 125 mA operating current. Here, the FSR under multi-peak injection locking conditions can also be tuned via effective birefringence of the Lyot filter from 25 to 300 GHz, as shown in Fig. 4(g). Under a fixed position of waveplates, the comb spacing is inversely proportional to the

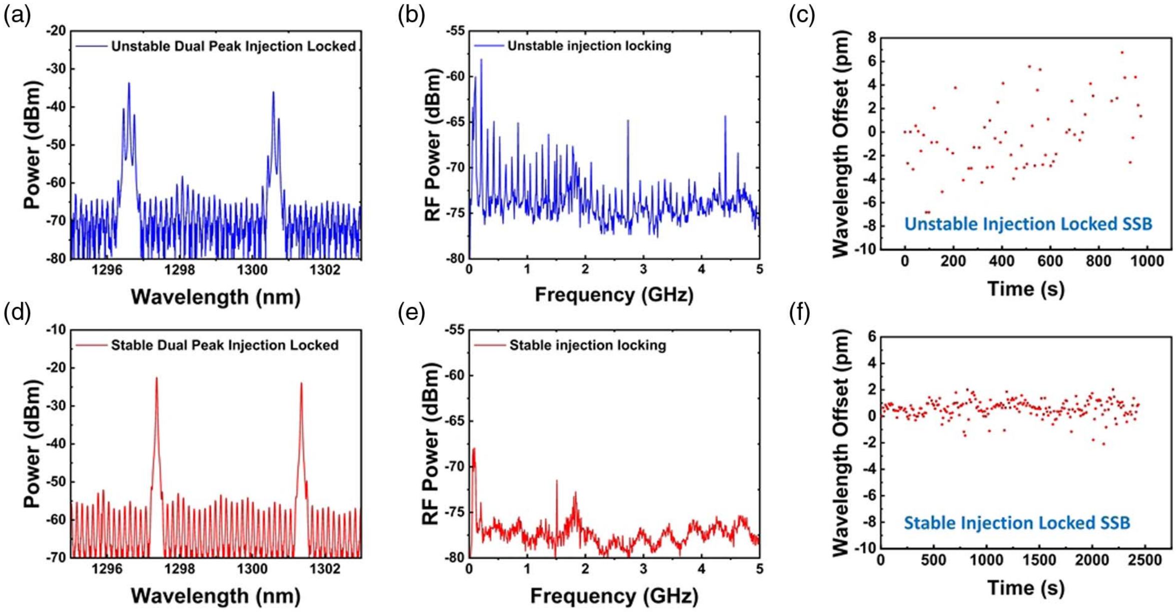

Fig. 5. (a) Optical spectrum, (b) RF spectrum, and (c) wavelength stability diagram of unstable dual-peak injection locked QDLSI. (d) Optical spectrum, (e) RF spectrum, and (f) wavelength stability diagram of stable dual-peak injection locked QDLSI.

effective length of the PMF. In Fig. 4(h), the relative intensity noise (RIN) is measured with an average RIN value of −135 dB/Hz for the SSB comb line, where the entire injection locked comb exhibits lower average RIN value of −145 dB/Hz within a 25 GHz span.

Furthermore, by tuning the FSR and wavelength dependent phase within the external cavity, we manage to achieve a dual-peak injection locked condition for QDLSI, as shown in Fig. 5. In order to verify the stability of multi-wavelength injection locking, a comb laser operating under both unstable and stable injection locking conditions is examined here, by fine tuning the waveplates of the PC into a dual-peak injection locking state. As shown in Fig. 5(a), multiple peaks exist on each partially locked mode, which is considered an unstable injection locked condition. By measuring the radio frequency (RF) spectrum in the range from 0 to 5 GHz [Fig. 5(b)], periodic chaotic oscillations are observed here, indicating that the comb laser is weakly or partially injection locked. The filtered SSB is then fed into a wavelength meter (Thorlabs OSA203) for stability measurements over time, as shown in Fig. 5(c), where there is approximately 14 pm (2.4 GHz in frequency) variation within 1000 s before moving into fully chaotic operation. In comparison, under stable dual-peak injection locking conditions, the optical spectrum exhibits two individual modes with FSR of exactly 700 GHz [Fig. 5(d)]. While measuring the RF spectrum, as shown in Fig. 5(e), strong chaotic resonance also disappears correspondingly. By taking a further wavelength stability test on stably injection locked QDLSI, here, we obtain less than 4 pm wavelength variation (700 MHz in frequency) for a much longer period of 2500 s, which indicates a reasonably good stability of dual-peak injection locking on QDLSI, as shown in Fig. 5(c).

Many narrow-linewidth comb sources on the Si platform have emerged recently [11,12,42,43] as potential on-chip optical sources for WDM communication, including heterogeneous passive MLLs and self-injection locked semiconductor lasers through an external high-Q MRR cavity, as shown in Table 1. Heterogeneous integrated III-V-on-Si/SiN passive

Table 1. Performance Comparison of Si-Based Comb Lasers

Operation Principle	Configuration	Optical Linewidth	Comb Spacing	10 dB Bandwidth (nm)	Ref.
Passive mode-locking	Ill-V-on-Si with extended Si cavity	400 kHz	100 MHz–1 GHz	12	[11]
Passive mode-locking	Ill-V-on-Si with extended SiN cavity	200 kHz	755 MHz	3.27	[12]
Passive mode-locking	Ill-V-on-Si with extended Si cavity	N/A	15.5 GHz	25	[44]
Mono-wavelength self-injection locking	lll-V DFB laser/SiN ring resonator	1.2 Hz	30 GHz	4	[19]
Mono-wavelength self-injection locking	lll-V FP laser/SiN ring resonator	370 Hz	12.5 GHz	N/A	[31]
Mono-wavelength self-injection locking	III V FP laser/SiN ring resonator	186 kHz	1.2 THz	N/A	[21]
Mono-wavelength self-injection locking	lll-V DFB laser/SiN ring resonator	1.1 kHz	25 GHz	N/A	[22]
Mono-wavelength self-injection locking	External cavity laser/lll-V DFB laser	20 kHz	14 GHz	N/A	[23]
Multi-wavelength self-injection locking (this work)	lll-V QD FP laser on Si/external Lyot filter	20 kHz	25–700 GHz (tunable)	13	

mode locked comb lasers appear to be the most compact solution to generate on-chip comb sources, but a relatively long external cavity leads to dense comb generation with low repetition rate. In comparison, self-injection locking with the assistance of a high-Q SiN MRR provides significantly narrowed optical linewidth, even towards the range of the hertz scale. In this case, it normally requires a narrow-linewidth seed laser (below 100 kHz), such as the external-cavity diode laser (ECDL). In this work, by implementing a simple QD FP laser diode epitaxially grown on Si with Lyot filter back-injection, a narrow-linewidth flat-top comb laser with tunable FSR and large 10 dB bandwidth is demonstrated. To the best of our knowledge, it is the first report of a multi-wavelength self-injection locked InAs QD FP laser on Si substrate with tunable FSR and large 10 dB bandwidth.

4. CONCLUSIONS

In general, we have demonstrated a multi-wavelength injection locking method of InAs QD laser on Si. Simultaneous multi-frequency locking with narrow linewidth is achieved from filtered back-injection with adjusted modal phase. There are maximum of 30 wavelength channels injection locked here, while the linewidth of each individual comb line is narrowed by three orders of magnitude from its original linewidth. This result paves a way towards compact and cost-effective narrow-linewidth comb sources for microwave photonics, photonic sensor systems, and quantum information applications.

Additional improvements beyond the results are also proposed here. For an integration perspective, the PMF-LMF can be replaced by lithium niobate on insulator (LNOI)-based multi-wavelength filters. As anisotropic material, lithium niobate exhibits optical birefringence [45], which makes it a desirable on-chip PC and tunable phase shifter [46,47]. We could precisely tune the birefringence of thin-film lithium-niobate-based Lyot filters with wavelength dependent phase control, therefore, achieving phase matched multi-wavelength injection. In next step, we will couple the comb light into Si waveguides on the chip-to-chip level to perform a more precise study. Meanwhile, we are also working on the monolithic integrated laser with Si waveguides. The integrated multi-wavelength injection locked laser on Si could enable the great potential of ultra-stable on-chip comb sources with tunable FSR for WDM telecommunication and microwave photonic applications.

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Data Availability. The data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

†These authors contributed equally to this paper.

REFERENCES

1. B. Corcoran, M. Tan, X. Xu, A. Beos, J. Wu, T. G. Nguyen, S. T. Chu, B. E. Little, R. Morandotti, A. Mitchell, and D. Moss, “Ultra-dense optical data transmission over standard fibre with a single chip source,” Nat. Commun. **11**, 2568 (2020).
2. H. Hu, F. D. Ros, M. Pu, F. Ye, K. Ingerslev, E. P. D. Silva, M. Mooruzzaman, Y. Amma, Y. Sasaki, T. Minzuno, Y. Miyamoto, L. Ottaviano, E. Semenova, P. Guan, D. Zibar, M. Galili, K. Yvind, T. Morioka, and L. K. Oxenlowe, “Single-source chip-based frequency comb enabling extreme parallel data transmission,” Nat. Photonics **12**, 469–473 (2018).
3. G. C. Liu, Z. G. Lu, J. R. Liu, Y. Mao, M. Vachon, C. Song, P. Barrios, and P. J. Poole, “Passively mode-locked quantum dash laser with 5.4 Tbit/s PAM-4 transmission capacity,” Opt. Express **28**, 4587–4593 (2020).
4. S. Liu, X. Wu, D. Jung, J. C. Norman, M. Kennedy, H. K. Tsang, A. C. Gossard, and J. E. Bowers, “High-channel-count 20 GHz passively mode-locked quantum dot laser directly grown on Si with 4.1 Tbit/s transmission capacity,” Optica **6**, 128–134 (2019).
5. J. Liu, E. Lucas, A. S. Raja, J. He, J. Riemnesberge, R. N. Wang, M. Karpov, H. Guo, R. Bouchand, and T. J. Kippenberg, “Photonic microwave generation in the X- and K-band using integrated soliton microcombs,” Nat. Photonics **14**, 486–491 (2021).
6. P. Del’Haye, A. Schliesser, O. Arcizet, T. Wilken, R. Holzwarth, and T. J. Kippenberg, “Optical frequency comb generation from a monolithic microresonator,” Nature **450**, 1214–1217 (2007).
7. T. J. Kippenberg, R. Holzwarth, and S. A. Diddams, “Microresonator-based optical frequency combs,” Science **332**, 555–559 (2011).
8. M. G. Suh and K. J. Vahala, “Soliton microcomb range measurement,” Science **359**, 884–887 (2018).
9. J.-Z. Huang, Z.-T. Ji, J.-J. Chen, W.-Q. Wei, J.-L. Qin, Z.-H. Wang, Z.-Y. Li, T. Wang, X. Xiao, and J.-J. Zhang, “Ultra-broadband flat-top quantum dot comb lasers,” Photon. Res. **10**, 1308–1316 (2022).
10. S. Chen, W. Li, J. Wu, Q. Jiang, M. Tang, S. Shutts, S. N. Elliott, A. Sobiesierski, A. J. Seeds, I. Ross, and P. M. Smowton, “Electrically pumped continuous-wave III–V quantum dot lasers on silicon,” Nat. Photonics **10**, 307–311 (2016).
11. Z. C. Wang, K. V. Gasse, V. Moskalenko, S. Latkowski, E. Bente, B. Kuyken, and G. Roelkens, “A III-V-on-Si ultra-dense comb laser,” Light Sci. Appl. **6**, e16260 (2017).
12. S. Cuyvers, B. Haq, C. O. Beeck, S. Peolman, A. Hermans, Z. Wang, A. Gocalinska, E. Pelucchi, B. Corbett, G. Roelkens, K. V. Gasse, and B. Kuyken, “Low noise heterogeneous III-V-on-silicon-nitride mode-locked comb laser,” Laser Photon. Rev. **15**, 2000485 (2021).
13. W. Q. Wei, J. Y. Zhang, J. H. Wang, H. Cong, J. J. Guo, Z. H. Wang, H. X. Xu, T. Wang, and J. J. Zhang, “Phosphorus-free 1.5 μm InAs quantum-dot microdisk lasers on metamorphic InGaAs/SOI platform,” Opt. Lett. **45**, 2042–2045 (2020).
14. Y. T. Wan, C. Xiang, J. Guo, R. Koscica, M. J. Kennedy, J. Selvidge, Z. Y. Zhang, L. Chang, W. Q. Xie, D. N. Huang, A. C. Gossard, and J. E. Bowers, “High speed evanescent quantum-dot lasers on Si,” Laser Photon. Rev. **15**, 2100057 (2021).
15. W. Q. Wei, Q. Feng, J. J. Guo, M. C. Guo, J. H. Wang, Z. H. Wang, T. Wang, and J. J. Zhang, “InAs/GaAs quantum dot narrow ridge lasers epitaxially grown on SOI substrates for silicon photonic integration,” Opt. Express **28**, 26555–26563 (2020).
16. D. Liang, S. Srinivasan, A. Descos, C. Zhang, G. Kurczveil, Z. H. Huang, and R. Beausoleil, “High-performance quantum-dot distributed feedback laser on silicon for high-speed modulations,” Optica **8**, 591–593 (2021).
17. Q. Feng, W. Q. Wei, B. Zhang, H. L. Wang, J. H. Wang, H. Cong, T. Wang, and J. J. Zhang, “O-band and C/L-band III-V quantum dot lasers monolithically grown on Ge and Si substrate,” Appl. Sci. **9**, 385 (2019).

18. Z. H. Wang, W. Q. Wei, Q. Feng, T. Wang, and J. J. Zhang, "InAs/GaAs quantum dot single-section mode-locked lasers on Si (001) with optical self-injection feedback," Opt. Express **29**, 674–683 (2021).
19. J. Warren, Q. F. Fan, L. Chang, B. Shen, H. Wang, M. A. Leal, L. Wu, M. Gao, A. Feshali, M. Paniccia, K. J. Vahala, and J. E. Bowers, "Hertz-linewidth semiconductor lasers using CMOS-ready ultra-high-*Q* microresonators," Nat. Photonics **15**, 346–353 (2021).
20. N. G. Pavlov, S. Koptyaev, G. V. Lihachev, A. S. Voloshin, A. S. Gorodnitskiy, M. V. Ryabko, S. V. Polonsky, and M. L. Gorodetsky, "Narrow-linewidth lasing and soliton Kerr microcombs with ordinary laser diodes," Nat. Photonics **12**, 694–698 (2018).
21. A. S. Raja, A. S. Voloshin, H. Guo, S. E. Agafanova, J. Liu, A. S. Gorodnitskiy, M. Karpov, N. G. Pavlov, E. Lucas, R. R. Galiev, A. E. Shitikov, J. D. Jost, M. L. Gorodetsky, and T. J. Kippenberg, "Electrically pumped photonic integrated soliton microcomb," Nat. Commun. **10**, 680 (2019).
22. A. S. Voloshin, N. M. Kontiev, G. V. Lihachev, J. Liu, V. E. Lobanov, N. Y. Dmitriev, W. Weng, T. J. Kippenberg, and I. A. Bilenko, "Dynamics of soliton self-injection locking in optical microresonators," Nat. Commun. **12**, 235 (2021).
23. W. L. Weng, A. Kaszubowska-Anandarajah, J. J. He, P. D. Lakshmijayasimha, E. Lucas, J. Q. Liu, P. M. Anandarajah, and T. J. Kippenberg, "Gain-switched semiconductor laser driven soliton microcombs," Nat. Commun. **12**, 1425 (2021).
24. A. Savchenkov, S. Williams, and A. Matsko, "On stiffness of optical self-injection locking," Photonics **5**, 43 (2018).
25. Z. C. Luo, A. P. Luo, W. C. Xu, H. S. Yin, J. R. Liu, Q. Ye, and Z. J. Fang, "Tunable multiwavelength passively mode-locked fiber ring laser using intracavity birefringence-induced comb filter," IEEE Photon. J. **2**, 571–577 (2010).
26. M. Imran, P. M. Anandarajah, A. Kaszubowska-Anandarajah, N. Sambo, and L. Potí, "A survey of optical carrier generation techniques for terabit capacity elastic optical networks," IEEE Commun. Surveys Tuts. **20**, 211–263 (2017).
27. J. Hillbrand, A. M. Andrews, H. Detz, G. Strasser, and B. Schwarz, "Coherent injection locking of quantum cascade laser frequency combs," Nat. Photonics **13**, 101–104 (2019).
28. L. Consolino, M. Nafa, F. Cappelli, K. Garrasi, F. P. Mezzapesa, L. Li, A. G. Davies, E. H. Linfield, M. S. Vitiello, P. D. Natale, and S. Bartalini, "Fully phase-stabilized quantum cascade laser frequency comb," Nat. Commun. **10**, 2938 (2019).
29. Q. Lu, D. Wu, S. Silvken, and M. Razeghi, "High efficiency quantum cascade laser frequency comb," Sci. Rep. **7**, 43806 (2017).
30. M. Piccardo, P. Chevalier, B. Schwarz, D. Kazakov, Y. Wang, A. Belyanin, and F. Capasso, "Frequency-modulated combs obey a variational principle," Phys. Rev. Lett. **122**, 253901 (2019).
31. N. Opačak, S. D. Cin, J. Hillbrand, and B. Schwarz, "Frequency comb generation by Bloch gain induced giant Kerr nonlinearity," Phys. Rev. Lett. **127**, 093902 (2021).
32. N. Opačak and B. Schwarz, "Theory of frequency-modulated combs in lasers with spatial hole burning, dispersion, and Kerr nonlinearity," Phys. Rev. Lett. **123**, 243902 (2019).
33. J. Hillbrand, D. Auth, M. Piccardo, N. Opačak, E. Gornik, G. Strasser, F. Capasso, S. Breuer, and B. Schwarz, "In-phase and anti-phase synchronization in a laser frequency comb," Phys. Rev. Lett. **124**, 023901 (2020).
34. S. J. Pan, J. O. Huang, Z. C. Zhou, Z. X. Liu, L. Ponnampalam, Z. Z. Liu, M. C. Tang, M. C. Lo, Z. Z. Cao, K. Nishi, K. Takemasa, M. Sugawara, R. Penty, I. White, A. Seeds, H. Y. Liu, and S. M. Chen, "Quantum dot mode-locked frequency comb with ultra-stable 25.5 GHz spacing between 20°C and 120°C," Photon. Res. **8**, 1937–1942 (2020).
35. L. P. Hou, Y. G. Huang, Y. H. Liu, R. K. Zhang, J. K. Wang, B. J. Wang, H. L. Zhu, B. Hou, B. C. Qiu, and J. H. Marsh, "Frequency comb with 100 GHz spacing generated by an asymmetric MQW passively mode-locked laser," Opt. Lett. **45**, 2760–2763 (2020).
36. J. Jung and Y. W. Lee, "Continuously wavelength-tunable passband-flattened fiber comb filter based on polarization-diversified loop structure," Sci. Rep. **7**, 8311 (2017).
37. O. Aharon and I. Abdulhalim, "Liquid crystal Lyot tunable filter with extended free spectral range," Opt. Express **17**, 11426–11433 (2009).
38. G. Sun, D. S. Moon, A. Lin, W. T. Han, and Y. Chung, "Tunable multi-wavelength fiber laser using a comb filter based on erbium-ytterbium co-doped polarization maintaining fiber loop mirror," Opt. Express **16**, 3652–3658 (2008).
39. J. Wang, K. Zheng, J. Peng, L. Liu, J. Li, and S. Jian, "Theory and experiment of a fiber loop mirror filter of two-stage polarization-maintaining fibers and polarization controllers for multiwavelength fiber ring laser," Opt. Express **17**, 10573–10583 (2009).
40. J. Ge and M. P. Fok, "Passband switchable microwave photonic multi-band filter," Sci. Rep. **5**, 15882 (2015).
41. L. Wang, H. Zhao, B. Shi, S. Pinna, S. S. Brunelli, F. Sang, B. Song, and J. Klamkin, "High performance 1.3 μm aluminum-free quantum dot lasers grown by MOCVD," in *Optical Fiber Communication Conference* (Optical Society of America, 2020), paper T4H-2.
42. C. Xiang, J. Liu, J. Guo, L. Chang, R. N. Wang, W. Weng, J. Peters, W. Xie, Z. Zhang, J. Riemensberger, J. Selvidge, T. J. Kippenberg, and J. E. Bowers, "Laser soliton microcombs heterogeneously integrated on silicon," Science **373**, 99–103 (2021).
43. C. Xiang, J. Guo, W. Jin, L. Wu, J. Peters, W. Xie, L. Chang, B. Shen, H. Wang, Q. F. Yang, D. Kinghorn, M. Paniccia, K. J. Vahala, P. A. Morton, and J. E. Bowers, "High-performance lasers for fully integrated silicon nitride photonics," Nat. Commun. **12**, 6650 (2021).
44. G. Kurczveil, A. Descos, D. Liang, M. Fiorentino, and R. Beausoleil, "Hybrid silicon quantum dot comb laser with record wide comb width," in *Frontiers in Optics* (Optical Society of America, 2020), paper FTu6E-6.
45. A. Kaushalram, G. Hedge, and S. Talabattula, "Mode hybridization analysis in thin film lithium niobate strip multimode waveguides," Sci. Rep. **10**, 16692 (2020).
46. Z. Lin, Y. Lin, H. Li, M. Xu, W. Ke, Z. Li, D. Wang, X. S. Yao, S. Yu, and X. Cai, "High performance polarization management devices based on thin-film lithium niobate," arXiv:2110.04508 (2021).
47. M. Xu, Y. Zhu, F. Pattala, J. Tang, M. He, W. C. Ng, J. Wang, Z. Ruan, X. Tang, M. Kuschnerov, L. Liu, S. Yu, B. Zheng, and X. Cai, "Dual-polarization thin-film lithium niobate in-phase quadrature modulators for terabit-per-second transmission," Optica **9**, 61–62 (2022).