Advances of Semiconductor Mode-locked Laser for Optical Frequency Comb Generation

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Special Topic:

**Advances of Semiconductor Mode-locked Laser for Optical Frequency Comb Generation**

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**Abstract:** Semiconductor mode-locked lasers (MLLs) can provide coherent optical frequency combs (OFCs) with high repetition rates and output power, which have been recognized as potential multi-wavelength sources used in optical communication field due to their compactness, high-efficiency, and low-cost properties. In this article, we have reviewed recent development of semiconductor MLL-based frequency comb generation. Different approaches of semiconductor MLL for OFC generation are synoptically summarized based on varies of material platforms. The representative progresses of III-V semiconductor MLLs on III-V platform and especially on Si substrates are both discussed for the applications in integrated silicon photonics.

**Keywords:** optical frequency combs, semiconductor mode-locked lasers, silicon-based photonic integrated circuits, monolithic and heterogeneous integration

**1 Introduction**

Over the past decade, following the emergence of mode-locked laser (MLL) [1] and high-Q micro-ring resonators, the optical frequency combs (OFCs) have attracted significant research interest owing to their outstanding optical properties. As known, OFCs were initially developed for precision measurements, such as optical ruler and atomic clocks [2-4]. By providing the combs with finest precision, OFCs can be utilized to conduct fine precision measurement since it can transfer phase and frequency information from stable references to optical domain, ultrafast pulse generation, calibration of atomic spectrographs [5]. The last decades witness numerous applications of OFCs in various fields, such as medical diagnostics [6], precision measurements [7, 8], gas spectroscopy [9, 10], and optical communications [11-14]. Meanwhile, in order to meet the desire of application divergence, different laser-based comb technologies are developed [15], including gain switched comb [16, 17], nonlinear fibers [18], high-Q microresonators [19, 20], electro-optic comb generators [21, 22], and semiconductor MLLs [23-27].

Nowadays, OFCs have been recognized as potential multi-wavelength sources used in optical communication field, which can provide up to thousands of optical channels from single comb laser applied in dense wavelength-division multiplexing (DWDM) systems [20, 28-30]. However, the traditional OFC-based technologies mainly rely on the bulky, power-hungry, complex, and expensive equipment to generate the comb lines, which will seriously restrict the application of them. Fortunately, with the rapid
development of silicon-based photonic integrated circuits (PICs) [31], the OFC light sources can be produced by utilizing the advanced nanofabrication techniques based on the micro-ring resonators [20]. Taken these advantages mentioned above, the OFC systems are coming to be much more compact, power efficient, and more economic [32]. Therefore, this leads OFC devices into the consumable applications, such autonomous driving [33], biological recognition [34], and 5G/6G communications [35].

During the development in last few decades, many achievements have been made to produce OFCs based on integrated photonics. Generally, there are two main categories in integrated photonics to generate comb sources: nonlinear frequency combs [36, 37] and semiconductor MLLs [23, 38]. For the nonlinear OFCs, various nonlinear optical media are adopted to generate the comb lines, such as Si [39], SiO$_2$ [40], Si$_3$N$_4$ [41], AlN [42], AlGaAs [43], LiNbO$_3$ [44], SiC [45], etc. Benefiting from the mature photonic platforms, nonlinear OFCs exhibit essential advantages of scalability, compactness, and low cost. On the other hand, the passive photonic devices generated OFCs always require the external optical pump lasers, which will bring drawbacks in some emerging on-chip application fields, that require monolithic integration and low power consumption [46]. As contrast, semiconductor MLLs are considered as a promising comb source for future PICs due to their improved compactness, low power consumption, great fabrication tolerance and cost efficiency [11, 31, 47].

In this article, we will focus on the semiconductor MLLs for generation of OFC light sources. Different comb-generating techniques of semiconductor MLLs will be compared here, while recent advances in integrated OFCs based on varies of material platform will be reviewed. The overall challenges and outlooks of integrated OFC sources in the near future will be discussed.

2 Overview of semiconductor mode-locked lasers

2.1 Fundamental mechanisms of semiconductor MLLs

As known, the semiconductor MLLs are a special type of diode lasers, which will provide coherent output comb lines with all the phase-locked longitudinal modes and equally-spaced frequency spectra [48]. All the optical modes in the OFC spectra can be described by the two basic metrics: repetition frequency and offset frequency. The repetition frequency defines the light emission frequency, and the offset frequency represents the additive frequency to achieve a harmonic and coherent operation among all optical modes. This offset comprises the difference in group velocity of different longitudinal modes so that they share a common phase and thus form laser pulses. Simply speaking, the repetition frequency represents the periodicity of the OFC line train. The offset frequency describes the phases of every individual mode, and allows fine optical frequency control. For most applications, the repetition rate should be suitable with the electronics used in signal detection and processing, which is usually owning the order of tens of gigahertz or less in RF frequencies.

So far, remarkable achievements have been made in the development of semiconductor MLLs. As following, the four mode-locking mechanisms about semiconductor MLLs will be briefly introduced.

Active mode locking: For active MLLs, a RF electrical modulation signal is applied by inserting the as-grown modulation gain section or an optical modulator in the laser cavity [49, 50] as shown in Fig. 1(a). As the frequency of the electrical modulation signal is close to the laser cavity roundtrip frequency, the gain of the laser is larger than the loss introduced by the modulator and the optical pulses can be achieved from the device. During operation, the complex longitudinal modes in the laser cavity will be modulated by the RF input and an equidistant modulation sideband mode will be acquired. At last, all the lasing modes will couple together by the frequency pulling effect [51] and stable mode-locked state will be presented. Active mode locking is favored in electro-optic applications, because the modulation strength and frequency can
both controlled by the electrical modulation signal to enable both frequency and phase modulation formats.

**Passive mode locking:** To obtain the passive mode locking mode, a saturable absorber (SA) is always introduced in the laser cavity as a nonlinear absorption component [52] as shown Fig. 1(b). The SA consists of a part of the active region, which is controlled by a reverse bias and electrically isolated from the laser gain section. As the conduction and valence of the laser SA section is fully filled with carriers coming from an optical pulse with high intensity, the SA part will be bleached and suppress further absorption of photons. Meanwhile, because of the absorption loss the continuous-wave (CW) optical source does not experience net gain, and the transient noise spike can bleach the absorption loss in the laser cavity to form a net gain window, ultimately leading to the building-up of pulse oscillation [48]. Moreover, the SA can also function as an attenuator which will shorten the duration of the pulses by absorbing the leading wing of the circulating pulse and balance other pulse broadening effect such as chromatic dispersion, resulting in an ultra-short pulse line. Owing to the desirable properties of passive mode locking described above, it has been being the most widely used mode-locking strategy recently.

For the passive mode locking, the SA section was set at the tail end of the laser, and the repetition rate is the same as the free spectral range (FSR) of the laser cavity. In actual applications requiring a higher repetition rate, the gain section cavity length must be shortened to increase the FSR, which is undesired because the optical gain of a shorter gain section may not be large enough to overcome the overall loss of the device. To address the issue, the colliding-pulse mode locking (CPML) strategy was introduced by inserting multiple SA sections at specific integer fractions of the cavity length to realize a harmonic mode-locking operation, which can enable up to hundreds of GHz repetition rates in cavities with a much lower fundamental frequency [53].

**Self-mode locking:** Different from active and passive mode locking methods, self-mode locking can be directly obtained only by a single-section laser structure without any modulation signals as shown in Fig. 1(c). Avoiding use of SA sections which will increase the intracavity loss of the laser, the OFCs generated by self-mode locking own higher power and efficiency. The most common self-mode locking behavior can be realized by strong four-wave mixing (FWM) within the active materials combined with the spatial hole-burning effect [54, 55] in a Fabry–Perot (FP) cavity. Due to this effect, one important application of self-mode locking is for mode-locked quantum cascaded lasers (QCLs) at longer lasing wavelength (> 3 μm) where the ultrashort excited-state lifetime prevents passive mode locking. Moreover, the self MLLs always exhibit superior coherence over other comb lines, and they do not necessarily produce single pulses with a uniform phase throughout the frequency spectrum.

**Self-injection mode locking:** Self-injection locking is a dynamic phenomenon representing stabilization of the emission frequency of a laser diode with a passive cavity enabling itself frequency-filtered coherent feedback to the laser cavity. Fig. 1(d) shows the schematic configuration of the self-injection MLLs with an external feedback reflector, such as optical fiber loop and high-Q resonators. Meanwhile, the linewidth of the laser could be decreased down to Hz range [56]. In this review, the Si-based InAs/GaAs QD self-injection MLLs will be demonstrated to generate OFCs with narrow line width and tunable spacing rates.
Figure 1 Four mode-locking mechanisms for semiconductor MLLs [50]. (a) The schematic configurations of the four mode-locking mechanisms: (a) active mode locking, (b) passive mode locking, (c) self-mode locking mode, and (d) self-injection mode locking.

2.2 Material platforms for semiconductor MLLs

Quantum well semiconductor MLLs:

The first integrated semiconductor MLL was demonstrated based on quantum well (QW) structures operating at 1.5 µm wavelength [38]. Over the past decades, with the significant development of semiconductor lasers, there have been many demonstrations of QW-based semiconductor MLLs with the lasing wavelengths covering the visible to near-infrared bands. Here, some research results of QW-based semiconductor MLLs will be reviewed according to the material categories.

InGaN/GaN [57]: By using a triple-section self-pulsating InGaN/GaN QW-based laser diode (SP-LD) operated by dc bias, the optical pulses were shortened to 15 ps with the emission wavelength of 402 nm and the optical peak power became as high as 10 W with a pulse repetition frequency of 1 GHz. This work provides a simple scheme to generate a picosecond optical pulse at a gigahertz repetition frequency without an external optical modulator component.

AlGaAs/GaAs [58]: The monolithic multi-sectioned AlGaAs/GaAs QW laser operating as multiple colliding pulse mode-locking source with lasing wavelength at around 868 nm was reported in ref. 56. A high-repetition rate pulse trains (up to 375 GHz) were achieved with the pulse width of about 1 ps. Moreover, the spectrum consisting of three modes gives a time-bandwidth product < 0.5.

AlGaInAs/InP [59]: By inserting a transparent passive waveguide in part of the AlGaInAs/InP QW laser cavity, the OFCs with 490-fs pulse width and 1550 nm-band light emission were achieved, which is the shortest pulse width reported based on QW MLLs. Moreover, several approaches are described for the harmonic mode-locking (HML) strategy: colliding pulse ML operating up to 240 GHz, coupled cavity ML up to 160 GHz, and sampled Bragg grating constructions up to 1.28 THz. These approaches offer a stable HML operating from 40 GHz to > 1 THz. Finally, the synchronized multi-wavelength ML laser array was demonstrated, which contains four 40-GHz lasers with designed wavelength registration used for optical code division multiple access or optical time division multiple access applications.

Quantum dot semiconductor MLLs:

Although QW-based semiconductor MLLs have been intensively investigated over the last two decades, the advent of quantum dot (QD) material systems has attracted many research attentions. Benefiting from the
three-dimension confinement of carriers, QDs exhibit a delta-function-like density of states, which enable unique physical properties of ultra-fast carrier dynamics, lower threshold current density, reduced sensitivity to crystalline defects, improved stability against optical feedback, and low temperature sensitivity [60-67]. Additionally, the semiconductor lasers with QD gain materials own the low relative intensity noise (RIN), leading to a large signal-to-noise ratio (SNR) and a low bit-error rate of the optical lines, which is required in the high-speed communication systems [68]. Furthermore, the inhomogeneous nature of the self-assembled QDs will broaden the gain spectrum, which is advantageous for broadband comb generation. Among all the attributes, one of the most notable properties is that the insensitivity to defects allows direct-epitaxial integration of high-quality QD MLLs on silicon substrates for PICs [69].

Typical QD-based structures (InAs/GaAs and InAs/InGaAsP) can cover the wavelength range from 1.1 μm to 1.8 μm, while for application at longer wavelengths (>3 μm), interband cascade lasers or quantum cascade lasers (QCLs) should be conducted. In terms of QCL based OFCs, it is challenging to achieve the standard two-section passive MLLs, due to the fast gain recovery (~0.3 ps) [70], which is much shorter than the cavity roundtrip time. While, the active or self-mode locking strategies can be applied to obtain combs from QCLs [71].

In the past decade, impressive achievements have been made in the field of InAs/GaAs or InAs/InGaAsP QD-based MLLs with high repetition rate ranging from tens to hundreds of gigahertz. Despite phenomenal success of semiconductor MLLs at the device level, incorporating the OFC sources into the PICs is still challenging. As known, there are two major approaches to integrate OFCs with other passive photonic components in PICs: monolithic or heterogeneous integration. Owing to the QD insensitivity to defects described above, epitaxial growth of QD-based light sources with telecom O and C band on complementary metal-oxide semiconductor (CMOS)-compatible Si (001) and SOI substrates is becoming possible, namely monolithic integration, which is considered as one of promising routes for future PICs. In comparison, heterogeneous integration of multiple photonic devices has great advantages of flexibility and relatively mature fabrication process, but can be challenging in large-scale foundry production [72].

Here, Table 1 summarizes some representative research results regarding III-V semiconductor comb sources [73-83]. Both the O-band and C-band III-V semiconductor mode-locked OFCs with high repetition rates and narrow linewidth are demonstrated.

<table>
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<tr>
<th>Operation Principle</th>
<th>Configuration</th>
<th>Optical Linewidth</th>
<th>Comb Spacing</th>
<th>Bandwidth</th>
<th>Ref. No.</th>
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<td>Passive Mode-locking</td>
<td>InGaAsP MQW with Extended Si Cavity</td>
<td>400 kHz</td>
<td>100 Mhz - 1 GHz</td>
<td>12 nm (10dB)</td>
<td>73</td>
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<tr>
<td>Passive Mode-locking</td>
<td>InP/InGaAs MQW with Extended SiN Cavity</td>
<td>200 kHz</td>
<td>755 MHz</td>
<td>3.27 nm (10dB)</td>
<td>74</td>
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<td>Passive Mode-locking</td>
<td>InAs/GaAs QD on SOI with External Cavity</td>
<td>N/A</td>
<td>102 GHz</td>
<td>6.5 nm (3dB)</td>
<td>75</td>
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<td>Passive Mode-locking</td>
<td>5th-order InAs/GaAs QD CPML on Si</td>
<td>N/A</td>
<td>100 GHz</td>
<td>N/A</td>
<td>76</td>
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<tr>
<td>Passive Mode-locking</td>
<td>Two-section InAs QD MLL</td>
<td>N/A</td>
<td>25.5 GHz</td>
<td>4.7 nm (6dB)</td>
<td>77</td>
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<tr>
<td>Passive Mode-locking</td>
<td>Two-section InAs QD MLL</td>
<td>N/A</td>
<td>94 GHz</td>
<td>3.18 nm (3dB)</td>
<td>78</td>
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<tr>
<td>Passive Mode-locking</td>
<td>4th-order InAs/GaAs MQW CPML</td>
<td>440 kHz</td>
<td>100 GHz</td>
<td>11.5 nm (3dB)</td>
<td>79</td>
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<td>Mono-wavelength Self-injection Locking</td>
<td>III-V DFB Laser/SiN Ring Resonator</td>
<td>1.2 Hz</td>
<td>30 GHz</td>
<td>4 nm (10 dB)</td>
<td>80</td>
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<tr>
<td>Mono-wavelength Self-injection Locking</td>
<td>III-V MQW FP Laser/SiN Ring Resonator</td>
<td>370 Hz</td>
<td>12.5 GHz</td>
<td>N/A</td>
<td>81</td>
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<tr>
<td>Mono-wavelength Self-injection Locking</td>
<td>III-V MQW FP Laser/SiN Ring Resonator</td>
<td>186 kHz</td>
<td>1.2 THz</td>
<td>N/A</td>
<td>82</td>
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<tr>
<td>Multi-wavelength Self-injection Locking</td>
<td>InAs QD FP Laser on Si/External Lyot Filter</td>
<td>20 kHz</td>
<td>30 GHz – 700 GHz (Tunable)</td>
<td>13 nm (10 dB)</td>
<td>83</td>
</tr>
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</table>

Table 1. Summary of III-V semiconductor mode-locked OFCs sources with high comb spacing.
3 III-V MLLs on GaAs and Si for Integrated Comb Source

3.1 Passive MLL comb source on GaAs (001) substrate

The passive mode locking is one of traditional methods to provide on-chip comb source due to its simplicity, handleability and compactness. The typical FP-cavity lasers can act as comb sources by introducing a saturable absorber (SA), which conducts as a nonlinear absorption component in the cavity [52]. In practice, the SA can be realized by reverse biasing one part of the active region of the FP laser, which should be electrically isolated from adjacent gain sections. Taking advantages of these specially designed passive mode-locking III-V semiconductor MLLs with single or multi SAs, great achievements have been made with tens to several hundreds of gigahertz repetition rates, which cover the O and C band telecommunication wavelengths [71, 74, 76, 84].

![Ultra-stable 25.5 GHz InAs/GaAs QD MLL on GaAs (001).](image)

Figure 2 Ultra-stable 25.5 GHz InAs/GaAs QD MLL on GaAs (001). (a) and (b) Schematic of the passive two-section MLL, and SEM image of the device showing the gap between the gain and SA. (c) Temperature dependent RF spectra. (d) Optical comb of the device at 100 °C.

Due to the delta-function-like density of states of QDs [85], the QD-based III-V lasers own high temperature stability, and high-temperature up to 220 °C continuous-wave (CW) operation has been reported for an InAs/GaAs QD FP laser [63]. Nowadays, with the rising demands of DWDM systems, the comb spacing of MLLs must be stable enough over an extremely broad temperature range. Stable mode-locking from 20 °C to 92 °C has been reported form a two-section InAs/GaAs QD passive MLL on GaAs [86], while, with a 20.5 GHz repetition rate, which is not large enough to meet the minimum requirement (e.g., 25GHz) of DWDM application. In 2020, the group from University College London demonstrated an ultra-stable frequency comb source based on a two-section InAs QD passive MLL with 25.5 GHz repetition rate over a broad temperature range of 20-120 °C [77]. Fig. 2(a) and (b) shows the schematic and SEM image of the passive two-section InAs/GaAs QD MLL device. The InAs QD laser structure was optimized to achieve high optical gain and large energy separation between GS (ground state) and ES (excited state),

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which will provide considerable output power and suppress the mode-locking switching between the two states at elevated temperature range. A 1615 μm long laser cavity with a 200 μm long SA was conducted to obtain a fundamental repetition rate of 25 GHz. The RF spectra (Fig. 2(c)) shows a 0.07 GHz change in mode spacing over the extremely broad temperature range from 20 °C to 120 °C, which is the broadest temperature range ever reported. A stable coherent comb spectrum with a lasing wavelength of 1349 nm and a 6 dB comb bandwidth of 4.81 nm was achieved at a high temperature of 100 °C (Fig. 2(d)), which enable a maximum of 31 potential channels with an OSNR of more than 36 dB. In order to achieve a larger mode-spacing (≥100 GHz), which is more desirable in the DWDM transmission systems, a short laser cavity is needed. The 100 GHz QD mode-locked OFC sources with 128 Gbit/s/λ PAM-4 transmission ability were also presented by using a similar passive two-section InAs QD MLL but with a short laser cavity of 405 μm [78, 84].

![Fourth-order 100 GHz colliding pulse mode-locked InAs/GaAs QD laser (CPML) on GaAs (001).](https://engine.scichina.com/doi/10.1360/nso/20220026)

However, limited by the small gain region of the MLL with short cavity, these comb sources cannot provide sufficient single channel output power, which is a key factor of the OFC systems. In typical optical links, high output power at each wavelength can enable a better system-level performance with higher SRN and lower bit error rate [29, 50]. Meanwhile, the optical amplifiers can be also integrated after the comb sources to boost up the optical power [87, 88]. To fundamentally solve this issue, the passive MLL with high-order CPML has been introduced recently [79]. As shown in Fig. 3(a), a fourth-order MLL design with 1580 μm cavity length and three SAs is implemented here to allow four colliding pulses traveling intracavity to produce fourth-order harmonic pulses at 100 GHz repetition rate. Top-flat spectra from the CPML laser can be achieved over a large temperature range from 20 °C to 100 °C (Fig. 3(b)). Under the
optimum operating condition, as large as twenty comb channels at 100 GHz spacing with 3 dB optical
bandwidth of 11.5 nm are obtained as shown in Fig. 3(c), which have a record average optical linewidth of
440 kHz from the CPML. The high-speed external modulation of a single channel (1321.28 nm) from the
fourth-order CPML was conducted as shown in Fig. 3(d), indicating open eye diagrams for 70 Gbits/s NRZ
and 80 Gbits/s PAM-4 modulation formats with extinction ratios of 4.4 dB and 6.4 dB, respectively. The
4.8 Tbit/s data transmission is expected from the single 100 GHz CPML with 36 nm broadband spectrum
containing maximum 60 channels over a variation of operation temperature. The CPML laser diode can
provide stable OFC lines with large comb spacing, large 3dB bandwidth and high output power, which
would be widely used in WDM systems, optical interconnects, and photonic neural networks.

3.2 MLL comb sources on Si platform

Compared with traditional fiber-based MLLs, the integrated MLLs on Si platforms provide the advantages
of small footprint, low cost and operation simplicity for the DWDM systems used in silicon photonic
integration. As mentioned above, both heterogeneous integration and monolithic integration play important
roles in future highly dense PIC depending on applications.

3.2.1 Heterogeneous integration MLLs on Si

Heterogeneous integrated MLLs on Si platforms have been extensively explored in the last decade. In the
year of 2007, the two-section passive MLL bonded to a Si substrate was demonstrated by Koch et al.,
which provides a C-band comb source with 40 GHz repetition rate and 4 ps pulses [25]. The external cavity
MLL was also employed to produce the comb lines with sharp linewidth and low phase noise. In 2017,
Wang et al. demonstrated a heterogenous ultra-dense MLL via III-V QW gain section bonded on silicon by utilizing DVS-BCB bonding method as shown in Fig. 4 [73]. As shown in Fig. 4(a) and (b), the MLL consists of a long Si spiral waveguide (37.4 mm) with low loss (0.7 dB/cm), two optical amplifiers separated by a SA, and two distributed Bragg reflectors (DBR) acting as the mirrors of the cavity. Fig. 4(c) shows the output spectrum when the laser is passively locked at 1 GHz repetition rate, indicating a 15 nm width 10-dB optical bandwidth and more than 1400 phase-locked comb lines. Recently, based on ultra-low loss Si$_3$N$_4$ external cavity, the III-V QW MLL on SOI with ultra-narrow RF linewidth was also reported by using the micro-transfer printing technique [74]. Cuyvers et al. demonstrated a heterogeneous integrated III-V-on-SiN passively mode-locked laser with a narrow 755 MHz comb spacing, RF linewidth of 1 Hz and optical linewidth below 200 kHz. As shown in Fig. 5(a), the ultra-low losses of Si$_3$N$_4$ waveguides acting as external cavity were employed and the InP/InAlGaAs multi-QW active devices are transferred to the Si$_3$N$_4$ passive cavity chip. Fig. 5(b) shows the RF spectrum of the passive MLL, presenting a top-flat densely-spaced RF comb spectrum with a 755 MHz line-spacing and exceeding 40 dB SNR. The zoom-in RF line with a center frequency of 755.2 MHz is shown in Fig. 5(c), which displays a qualitative $-10$ dB RF linewidth of 300 Hz. The narrow RF linewidth indicates that all optical modes are tightly phase-locked. Additionally, the III-V QD-based MLLs were also realized on SOI substrates by Hewlett-Packard Laboratories via bonding technique [89-91]. The hybrid-silicon III-V quantum dot colliding pulse mode-locked lasers showed an error-free operation in multiple modes with extinction ratios of 11.5 dB, which can act as useful light sources with high-reliability in WDM optical links [90, 91]. These results presented here proved a successful integration of ultra-low loss passive waveguides and III-V MLLs on SOI platform with massive comb channels and ultra-low phase noise.

Figure 5 Heterogeneously integrated III-V-on-silicon-nitride passively MLLs. (a) Schematic of the device (upper) and microscope image.
of the III-V waveguide (lower). (b) RF spectrum of the generated pulse train. (c) Zoom-in of the repetition frequency signal with a center frequency of 755.2 MHz.

3.2.2 Monolithic integration MLLs on Si

Although heterogeneous integrated III-V lasers on Si have been extensively demonstrated recent years, monolithic integration has been considered as an alternative solution to integrate III-V light sources including MLLs on Si with high density and compactness. Due to the physical mismatch between III-V and Si, it is challenging to realize high-quality III-V materials epitaxially grown on Si substrates.

- III-V layers epitaxy on Si (001) substrates

In terms of epitaxial growth III-V on Si, three major issues must be solved: threading dislocations (TDs), antiphase boundaries (APBs), and thermal cracks [92, 93]. In last 20 years, many techniques have been utilized for achieving high-quality III-V materials on IV substrates, and prominent achievements have been made towards high-performance InAs/GaAs QDs lasers grown on Si substrates with telecommunication wavelengths [94-98]. The off-cut silicon substrates (Fig. 6(a)) were first used to avoid the formation of APBs when III-V grown on Si, by producing double-atomic step surface under routine annealing process [94, 95]. High-performance 1300 nm InAs/GaAs QD laser with a low threshold current density of 62.5 A cm\(^{-2}\) was then grown and fabricated on these substrates [99]. The patterned Si (001) substrates with high Miller index surfaces are also applied to avoid the APBs as shown in Fig. 6(b) [100]. In addition, optimized AlGaAs nucleation layer [97] and special substrate surface treatments [101] are also adopted to avoid the APB formation as shown in Fig. 6(c) and (d). However, most techniques focused on the TD and APB suppressions, the thermal crack issue remains unsolved.

![Figure 6 Techniques for epitaxial growth of III-V on Si platforms.](image)

In 2018, Wei et al. demonstrated a novel epitaxial method by molecular beam epitaxy (MBE) to construct the (111)-faceted silicon hollow structures on the “U”-shape patterned Si (001) substrates, and high-quality GaAs layers were achieved on Si (001) (Fig. 7) [102]. As the cross-sectional TEM image shows in Fig 7(d), the homoepitaxially-formed sawtooth structures can be effective to suppress APBs and reduce the TDs. From the AFM and ECCI measurement results shown in Fig. 7(e) and (f), no APBs were observed on the surface and a smooth GaAs layer with a 1.3 nm roughness (root-mean-square, RMS) and a
4.8×10^6 cm^-2 threading dislocation density was obtained after deposition of 2 μm III-V buffer on these specially designed Si (001) substrates. Moreover, the high-quality GaAs/SOI templates were also demonstrated by using the same method, and InAs/GaAs QD lasers were first grown and fabricated on SOI [103-105]. More importantly, the voids under the sawtooth structures shown in Fig. 7(c) are experimentally proved to be able to release the thermal stress of the whole sample, avoiding the thermal crack formation. These high-quality GaAs/Si (001) platforms enable the possibility of growing and fabricating high-performance integrated InAs/GaAs QD light sources on CMOS-compatible Si (001) and SOI substrates for the applications in PICs.

![Figure 7](https://engine.scichina.com/doi/10.1360/nso/20220026)

**InAs/GaAs QD MLLs grown on Si (001) substrates**

Owing to the dramatic progress in direct epitaxial growth of III-V on Si, the first passively mode-locked QD laser grown on Si substrates was demonstrated by Liu et al. in 2019 [69]. Fig. 8(a) shows the schematic diagram of the epitaxial structure on Si (001) substrate, including a 5-layer chirped QD active region in order to broaden the spectral bandwidth of the MLL. The 20 GHz two-section passive mode-locking design was conducted by using a 2048 μm cavity length with a 287 μm SA section as shown in Fig. 8(b). Fig. 8(c) shows the square-like optical spectrum with the largest 3 dB bandwidth of 6.1 nm (58 lines, 80 lines within 10 dB) under optimized mode locking state of the Si-based MLL. A record low timing jitter value for the Si-based MLL of 82.7 fs (4–80 MHz) and a narrow RF 3 dB linewidth of 1.8 kHz are achieved as shown in Fig. 8(d) and (e). Although limited by the low repetition rate of 20 GHz, this work paves the way to integrate the on-chip MLL comb sources.
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Figure 8 Si-based passively mode-locked 20 GHz QD-MLL. (a) and (b) Schematic diagrams of the epitaxial structure and the 20 GHz MLL device of quantum dot mode-locked laser on silicon, respectively. (c) Optical spectrum and corresponding optical linewidth of each mode within 10 dB. (d) RF spectrum in a 50 GHz span view. (e) The single-sideband phase noise plot under the narrowest pulse width condition.

As known, in order to achieve high repetition rate MLL comb sources to avoid channel crosstalk, short laser cavity is need, which suffers from reduced optical gain, especially for the lasers grown on Si substrates. It is difficult to obtain high-performance two-section InAs/GaAs QD passive MLL with high repetition rate (≥ 100 GHz) direct grown on Si substrate. In addition, MLL itself as an active comb source regularly experience current and thermal induced frequency variation. Therefore, the self-mode locked QD lasers with assistance of self-mode locking technique can provide OFCs with narrowed optical linewidth, improved frequency and phase stability. Fig. 9 shows a self-injection MLL, based on a standard InAs/GaAs QD FP laser grown on Si (001) substrate (Fig. 9(a)) [27]. By introducing an optimized self-injection strength and proper phase, the RF linewidth of the MLL was significantly narrowed by two orders of magnitude from 900 kHz to 8 kHz as shown in Fig. 9(c). For on-chip applications, this single-section Si-based InAs QD-MLL via optical self-injection can be realized by integrating a silicon photonic feedback loop with the laser diode to achieve coherent feedback conditions.

Figure 9 Si-based self-injection mode locked InAs/GaAs QD laser. (a) Color-enhanced SEM image of an initial Si-based ridge laser with the ridge width of 4 μm. (b) Evolution of the RF spectra with different feedback strength. (c) The comparison of the RF spectra at 23.4 GHz of the MLL at mode-locked mode and free running mode.

The multi-wavelength injection locking of InAs/GaAs quantum dot FP lasers grown on silicon by optical self-injection via an external cavity was demonstrated recently as shown in Fig. 10 [83]. By using chirped InAs QDs, an ultra-broad flat-top OFC spectrum was achieved from the FP laser on the Si substrate at the self-injection condition maintained by an external polarization-tunable fiber cavity as shown in Fig. 10(a). The number of locked laser modes can be fully adjusted from single peak to multiple peaks by tuning wavelength dependent phase and mode spacing of back-injected light through Lyot filter, and the free spectral range (FSR) of the OFCs is tunable from approximately 50 GHz to 750 GHz. As shown in Fig.
10(b) and (c), at a low injection current of 75 mA, 10 self-injection locked peaks at comb spacing of 75 GHz (third-order) are achieved. While increasing the injection current up to 125 mA, relatively broad 3 dB bandwidth is presented in the original optical spectrum, therefore, the number of injection locked comb lines is also increased to 30. Here, the -10 dB bandwidth measured here is approximately 13 nm. Moreover, the optical linewidth of the combs is significantly narrowed by more than two orders of magnitude. It is the first report of multi-wavelength self-injection locked InAs QD FP laser on Si substrate with tunable FSR and large 10 dB bandwidth.

![Figure 10](https://engine.scichina.com/doi/10.1360/nso/20220026)

Figure 10: Si-based multi-wavelength self-injection InAs/GaAs QD MLLs with an external fiber cavity. (a) The schematics of chirped InAs QD laser on Si self-injection locked into multiple wavelengths via PM fiber based external cavity. Original optical spectrum (b) and the multi-wavelength injection locked comb spectrum (c) of the MLL operated at a low injection current of 75 mA. Original optical spectrum (d) and the multi-wavelength injection locked comb spectrum (e) of the MLL operated at a high injection current of 125 mA.

By implementing a standard QD FP laser diode epitaxially grown on Si with Lyot filter back-injection, narrow-linewidth flat-top comb laser with tunable FSR and large 10-dB bandwidth is demonstrated. Overall, Chen et al. reported multi-wavelength self-injection locked InAs QD FP laser on Si substrate with tunable comb spacing depending on phase locking [83]. These results pave a way towards tunable narrow-linewidth comb source for microwave photonics, photonic sensor system and quantum information applications.

### 4 Conclusion and Outlook

In this article, we have reviewed recent development of semiconductor MLL-based frequency comb generation. To compare with Kerr frequency combs, semiconductor MLLs exhibit essential advantages in comb power and power efficiency, but relative narrow gain bandwidth leads to their limited applications.
Over octave bandwidth offers Kerr OFCs strong capability in precision measurements and sensing applications, but the sech² nature of soliton comb, which gives a large variation in single channel output power, that remains as a major drawback in WDM photonic interconnect applications. Therefore, at current stage, MLL-based OFCs remain their advantages in foreseeable application fields such as DWDM telecommunications and optical interconnects. In order to extend the applications for semiconductor MLL generated comb sources, material system with enlarged gain bandwidth need to be extensively developed in future research, such as chirped QD system or regrowth of multiple gain sections with extended wavelength. Overall, both semiconductor MLL and Kerr OFCs exhibit their own unique physical properties that enable their targeted applications.

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Conflict of interest

The authors declare that they have no conflict of interest.

Data availability

The original data are available from corresponding authors upon reasonable request.

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