NRC·CNRC

NRC Publications Archive
Archives des publications du CNRC

Passively mode-locked quantum dash laser with an aggregate 5376 Tbit/s PAM-4 transmission capacity

Liu, Guocheng; Lu, Zhenguo; Liu, Jiaren; Mao, Youxin; Vachon, Martin; Song, Chunying; Barrios, Pedro; Poole, Philip J.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.
For the publisher's version, please access the DOI link below./ Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:
https://doi.org/10.1364/OE.386266
Optics Express, 28, 4, pp. 4587-4593, 2020-02-17

NRC Publications Archive Record / Notice des Archives des publications du CNRC :
https://nrc-publications.canada.ca/eng/view/object/?id=b9585b52-72b3-468f-81a4-f768fda776f4
https://publications-cnrc.canada.ca/fra/voir/objet/?id=b9585b52-72b3-468f-81a4-f768fda776f4

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada | Conseil national de recherches Canada

Canada

Research Article | Vol. 28, No. 4 / 17 February 2020 / Optics Express 4587
Optics EXPRESS

Passively mode-locked quantum dash laser with an aggregate 5.376 Tbit/s PAM-4 transmission capacity

GUOCHENG LIU,* ZHENGUO LU, JIAREN LIU, YOUXIN MAO, MARTIN VACHON, CHUNYING SONG, PEDRO BARRIOS, AND PHILIP J. POOLE

Advanced Electronics and Photonics Research Centre, National Research Council, Ottawa, ON, Canada
*guocheng.liu@nrc-cnrc.gc.ca

Abstract: This paper presents an InAs/InP quantum dash (QD) *C*-band passively mode-locked laser (MLL) with a channel spacing of 34.224 GHz. By using this QD-MLL we demonstrate an aggregate 5.376 Tbit/s PAM-4 data transmission capacity both for back-to-back (B2B) and over 25-km of standard single mode fiber (SSMF). This represents the first demonstration of QD-MLL acting as error-free operation at an aggregate data transmission capacity of 5.376 Tbit/s for some filtered individual channels. This finding highlights the viability for InAs/InP QD lasers to be used as a low-cost optical source for data center networks.

1. Introduction

The high demand for ultrahigh-speed optical networks within and between data centers results in intensive efforts in the development of new advanced photonics components towards the realization of greater than 1 Tbit/s transmission capacity [1–3]. The use of wavelength division multiplexing (WDM) and advanced modulation formats [2] is becoming more and more attractive to alleviate transmission bottlenecks. Dense-WDM (DWDM) at 1.55 µm as well as erbium doped fiber amplifiers (EDFAs) to compensate for span loss are preferred in order to achieve the capacity objectives. Among these advanced modulation formats, four-level pulse amplitude modulation (PAM-4) has obtained significant attention because of its simplicity and reliable performance [4] compared to other formats such as orthogonal frequency division multiplexing/16-quadrature amplitude modulation (OFDM/16-QAM) [5] and multi-band carrierless amplitude phase modulation (multi-CAP) [6]. Besides the requirements for higher data rate, a compact, low-cost, energy-efficient semiconductor comb laser is further desired [7]. Quantum-dot and dash (QD) based semiconductor mode-locked lasers (MLLs) are a promising solution for next generation high speed optical networks and optical signal processing [7] due to their advantages such as stable optical pulse trains at high repetition rates, narrow pulse widths, compact size, low power consumption, simple fabrication, and the ability for hybrid integration with silicon substrates [8]. Moreover, they offer reduced spontaneous emission rates and low threshold current densities which leads to reduced intrinsic noise [7–9].

Various demonstrations have been carried out to show the potential of QD mode locked lasers (QD-MLLs) for Tbit/s transmission [4,5,7,8,10–12]. Operating in the *O*-band (1.3 µm) wavelength range at room temperature, direct epitaxial growth of GaAs layers onto silicon substrate with InAs QD active material provides an appealing direction by enabling QD-MLL integration with silicon complementary metal-oxide-semiconductor (CMOS) technology [8]. However, direct bandgap III-V semiconductors exhibit a large lattice mismatch and/or strongly differing thermal expansion coefficient with silicon, which leads to high-density defects of threading dislocations [13,14]. In contrast, InP-based growth technology is very promising for QD lasers operating in the *C*-band (1.55 µm) regime [15]. Furthermore, InP-based QD-MLLs can be integrated with EDFAs in optical networking systems. For example, using ~40 channels with 33.6 GHz InAs/InP QD-MLLs, the obtained performance for standard 28 GBaud PAM-4

#386266 https://doi.org/10.1364/OE.386266
Journal © 2020 Received 23 Dec 2019; revised 24 Jan 2020; accepted 26 Jan 2020; published 3 Feb 2020

Optics EXPRESS

signal shows calculated bit-error-rate (BER) performance of 5×10^{-6} after transmission over 3-km of SSMF [4].

In recent years we have reported several InAs/InP QD-MLLs operating in the *C*-band [16–18]. In this paper, we have developed an InAs/InP QD-MLL with the channel spacing of 34.224 GHz. We have investigated its relative intensity noise (RIN), phase noise, and RF beating signal. The integrated average RIN, from 10 MHz to 10 GHz, for the whole lasing spectrum was measured to be -160.5 dB/Hz. For individual channels the integrated average RIN can be as low as -129.5 dB/Hz, with the average of all 48 channels between 1547.855 nm to 1560.812 nm being approximately -128 dB/Hz. The measured average optical linewidth is 1.55 MHz, ranged from 620 kHz to 4.2 MHz, and the 3-dB mode beating RF linewidth is 1.688 kHz. Using this QD-MLL we demonstrate 5.376 Tbit/s (PAM-4 48 × 28 GBaud PDM) aggregate data transmission capacity both for back-to-back (B2B) and over 25-km of SSMF configuration with error-free operation. So far, this is the highest reported aggregate data transmission capacity using a single semiconductor laser chip and PAM-4 modulation format for data center network applications.

2. Experimental configuration

The InAs/InP QD material was grown by chemical beam epitaxy (CBE) on exactly (001)-oriented *n*-type InP substrates [19]. A 355 nm thick InGaAsP waveguide core contained five stacked layers of InAs QDs with $In_{0.816}Ga_{0.184}As_{0.392}P_{0.608}$ (1.15Q) barriers as the gain medium, surrounded by *n*- and *p*- type InP cladding layers. The average QD density was approximately 3.5×10^{10} cm^{-2} per layer. Single lateral mode ridge waveguide QD-MLLs were fabricated with a stripe width of 2.0 μm and a Fabry-Perot (FP) laser cavity length of 1227 μm via standard photolithography and combination of dry-, wet-etching and contact metallization techniques. Figure 1(a) shows a scanning electron microscope (SEM) image of the facet of a processed laser and a corresponding schematic cross-section is shown in Fig. 1(b). The laser was mounted on a copper block, DC-driven with an ultra-low noise laser driver, and temperature controlled by a thermo-electric cooler (TEC) maintained at 17°C (ILX Lightwave, Model LDC-3724C). To study the passive mode-locking behavior of the laser, the output spectrum was characterized using an optical spectrum analyzer (Anritsu, Model AQ6317B), RF performance was measured using a 50 GHz PXA signal analyzer (Keysight Technologies, Model N9030A) with a 45 GHz IR photodetector (New Focus, Model 1014), and RIN and phase noise were recorded with an Agilent N4371A relative intensity noise measurement system and an OE4000 automated laser linewidth/phase noise measurement system (OEWaves Inc.).

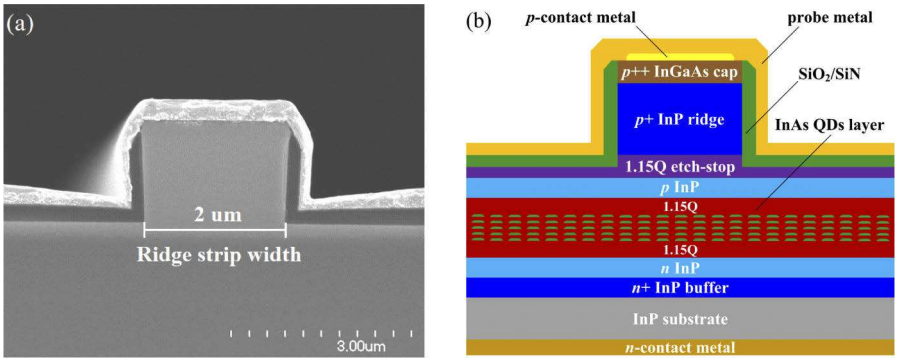

Fig. 1. (a) Cross-sectional scanning electron microscopy image showing the facet of a fabricated Fabry-Perot (FP) InAs/InP QD laser; (b) Schematic cross-sectional diagram of a shallow-etched ridge-waveguide InAs/InP QD laser.

Optics EXPRESS

The QD-MLL emitted a multi-wavelength comb within the *C*-band. Each wavelength channel of the comb was selected by an optical bandpass filter (OBPF) (Santec, Model OTF-350) as an optical carrier and an erbium-doped optical fiber amplifier (EDFA) (Amonics, Model AEDFA-PA-35-B-FA) was used to amplify the carrier power up to ~10 dBm. This optical carrier signal was launched into a dual polarization (DP) I/Q optical modulator (SHF Communication Technologies AG, Model SHF 46215B DP-QAM) for data modulation. A modulated 28 GBaud PAM-4 optical signal was created using an arbitrary waveform generator (AWG) (Keysight Technologies, Model M9502A). The signal was boosted using another EDFA (Amonics, Model AEDFA-BO-23-B-FA) and transmitted both for B2B configuration and over 25-km of SSMF. Finally, after optimizing the power and signal using EDFA, OBPF, and a variable optical attenuator (VOA) (Agilent, Model 8156A), the received signal was processed by an integrated optical modulation analyzer (Keysight Technologies, Model N4392A).

3. Results and discussion

3.1. InAs/InP QD laser performance

Figure 2(a) shows the lasing optical spectrum, which exhibits a center wavelength of 1554.22 nm and a 6-dB comb bandwidth of 12.96 nm, providing 48 channels with an optical signal-to-noise ratio (OSNR) of more than 40 dB. RF performance is presented in Fig. 2(b) showing a sharp fundamental RF beating frequency at 34.224 GHz and a signal to noise floor ratio (SNR) larger than 45 dB. The inset shows the RF linewidth with a Lorentzian fit. The 3-dB linewidth is 1.688 kHz, and such an extremely narrow linewidth leads to excellent pulse-to-pulse time jitter value (2.59 fs) [10] and phase noise characteristics [15].

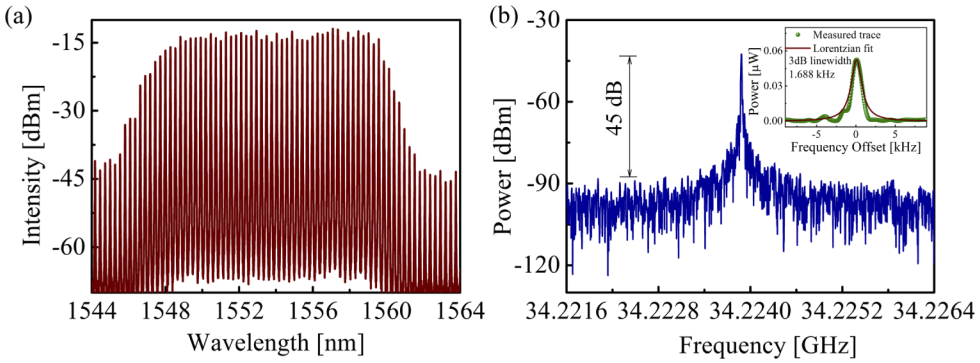

Fig. 2. (a) Optical output spectrum of a QD-MLL with a ridge width of 2 μm and cavity length of 1227 μm, measured at 330 mA and 17°C (Noise floor: -60 dBm and resolution bandwidth (RBW): 0.01 nm); (b) RF beating frequency of 34.224 GHz between any two adjacent channels (RBW: 5 kHz). The inset is the narrow span RF peak with Lorentzian fit (RBW: 1 kHz).

Figure 3(a) shows the RIN spectra in the frequency range from 10 MHz to 10 GHz for both the whole lasing spectrum and three filtered channels. We achieve an integrated average RIN value less than -160.5 dB/Hz for the whole laser, with the upper bound set by the instrument limited RIN measurement floor. For three filtered channels like 1557.484 nm, the integrated average RIN value increases to about -129.5 dB/Hz due to mode partition noise. The low frequency RIN does not exceed -116 dB/Hz for our device unlike the measurements shown in Ref. [4] which is up to -90 dB/Hz. Such a low RIN value is attributed to the characteristics of QD material inside the laser cavity. Figure 3(b) shows the measured integrated average RIN for individually filtered comb lines. The integrated RIN values for the 48 filtered individual channels in the frequency

Optics EXPRESS

range from 10 MHz to 10 GHz are approximately -128 dB/Hz, in the range from -125 dB/Hz to -130 dB/Hz. The reason for higher RIN in the center of the lasing spectrum is possibly due to several nonlinear optical effects such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave-mixing (FWM) within the F-P cavity [18]. Figure 3(c) shows the optical linewidth of each of the filtered individual channels from 1547.855 nm to 1560.812 nm at 330 mA and 17°C. The average optical linewidth of each mode is around 1.55 MHz, measured using a delayed self-heterodyne interferometer. A small increase in optical linewidth is observed in the center of the spectrum reflecting the behavior observed in the RIN. The left inset is a comparison of the frequency noise spectra from three filtered wavelength channels at 1551.824 nm, 1552.924 nm and 1553.474 nm. The right inset is the single-sideband (SSB) phase noise measurement of the RF beating signal in the range from 100 Hz to 1 MHz. A strongly suppressed phase noise is observed over the entire frequency range of the carrier offset. The performance is believed to benefit from the low amplified spontaneous emission (ASE) noise and low confinement factor properties of the QD-MLL material.

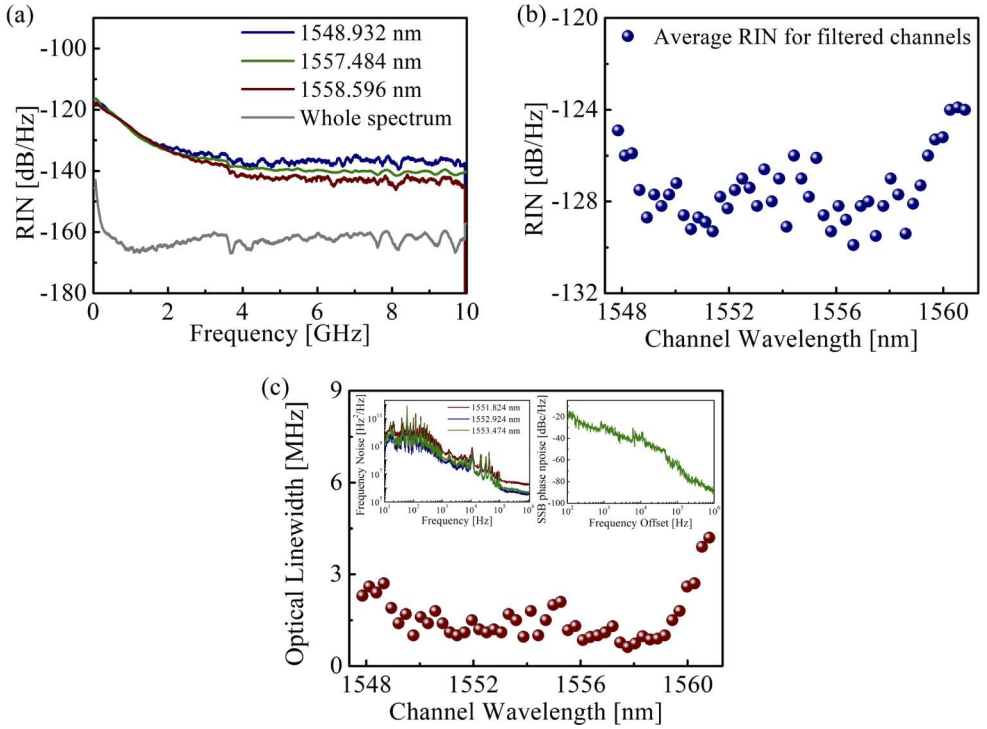

Fig. 3. (a) Measured RIN for the whole laser and three filtered channels in the frequency range from 10 MHz to 10 GHz. (b) Measured integrated average RIN of the QD-MLL for individually filtered comb lines in the frequency range from 10 MHz to 10 GHz; and (c) Optical linewidth of the filtered individual channels from 1547.855 nm to 1560.812 nm at 330 mA and 17°C. The left inset is a comparison of the frequency noise spectra from three filtered wavelength channels of 1551.824 nm, 1552.924 nm and 1553.474 nm. The right inset is the single-sideband (SSB) phase noise of the RF beating signal at 330 mA and 17°C.

3.2. *Data transmission performance*

Figure 4(a) shows the experimental setup for the PAM-4 data transmission. At the dual polarization (DP) I/Q optical modulator side (T_X), a 28 GBaud PAM-4 base-band signal is created by using an AWG generating a pseudo-random bit sequence (PRBS) with a pattern length of 2^{15}-1 bits at

Optics EXPRESS

a symbol rate of 28 Gbit/s non-return to zero (NRZ) on two uncorrelated channels (*IY/IX*). A root-raised-cosine (RRC) filter is applied with the roll-factor of 0.35 for Nyquist pulse filtering. Thermally stable nested lithium niobate ($LiNbO_3$) Mach-Zehnder modulators (MZMs) of the I/Q optical modulator are driven by the AWG for data modulation. At the receiver side (R_X), the modulated signal is first amplified by $EDFA_3$, and the optical bandpass filter $OBPF_2$ is used to filter out the ASE from the EDFA. The Keysight optical modulation analyzer (OMA) coherently receives the signals using a free-running local oscillator (LO). Combined with the software package offered by the OMA, a matched RRC filter is executed to mitigate the effects of white noise. The digitized signals undergo a number of digital signal processing (DSP) steps, including timing recovery, frequency offset compensation, carrier phase compensation, Kalman filtering, and adaptive equalization. Finally, the output PAM-4 signal is decoded for error vector magnitude (EVM) measurement and BER evaluation. The BER performance is evaluated based on the EVM measurement. A variable optical attenuator (VOA) can be added before the optical modulation analyzer to control the received optical power. The inset shows the optical spectra of one filtered channel at 1552.924 nm, at the output before modulation and after PAM-4 modulation. The modulated optical signal is transmitted both for B2B configuration and over 25-km SSMF, respectively.

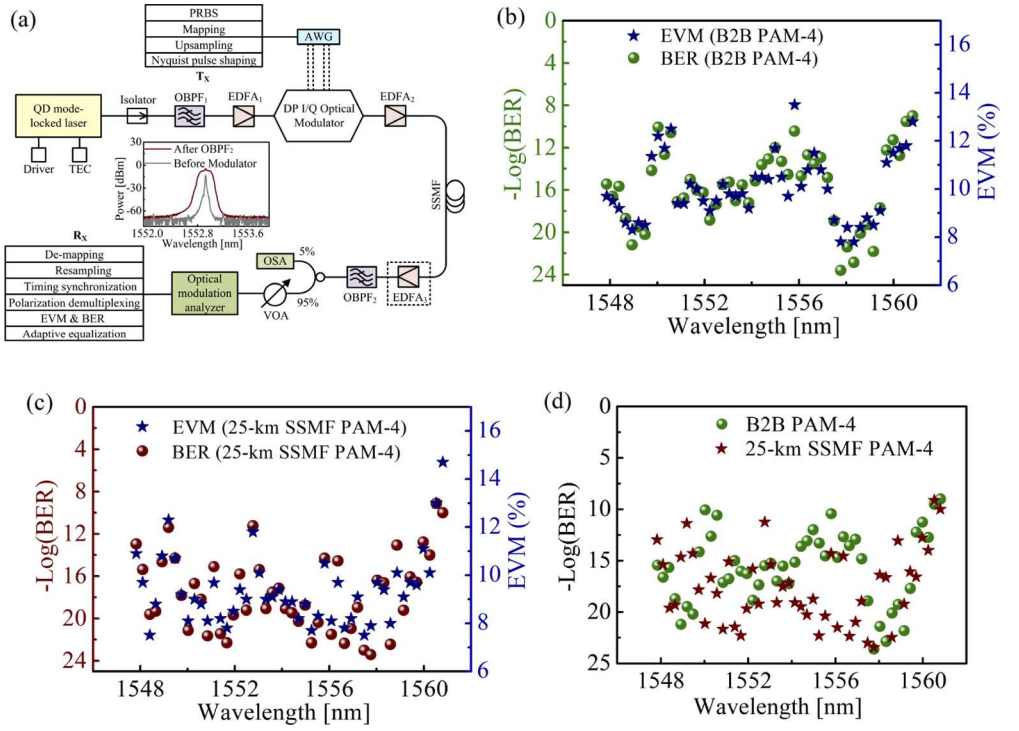

Fig. 4. (a) PAM-4 data transmission setup with the DP I/Q optical modulator (T_X) and the receiver (R_X). $EDFA_3$ is only used for 25-km SSMF transmission. The inset shows the OSA spectra of one filtered channel at 1552.924 nm, include after $OBPF_2$ and before optical modulator; (b-c) Measured EVM and corresponding BER evaluation; and (d) BER evaluation for B2B and after 25-km of SSMF transmission.

Figures 4(b) and (c) show the measured EVM and corresponding BER evaluation at the same received optical power of -15 dBm for all individual channels. The EVMs are 7.8 - 13.5% [Fig. 4(b)], and 7.5 - 14.7% [Fig. 4(c)], respectively, after B2B and 25-km SSMF transmission (chromatic dispersion of 17 ps/nm/km). Some channels exhibit the BERs performance below

Optics EXPRESS

the error-free operation limit (BER = 1.0×10^{-9}) [20]. At some channels in Fig. 4(d), the performance after 25-km SSMF transmission are better than that of B2B configuration due to the dispersion of fiber would cancel the effect of the chirp induced by the optical modulator [21,22]. Using a VOA before the optical modulation analyzer to control the received optical power, Fig. 5(a) shows the dependence of BER evaluation on received optical power for the carriers located at 1557.484 nm and 1547.855 nm for B2B and after 25-km of SSMF transmission. The power penalty at BER of 10^{-9} is free for the measured channel at 1557.484 nm and 1.5 dB for the channel at 1547.855 nm. The BER floors can be observed around -15 dBm. One of the comb lines chosen (1547.855 nm) is at the short wavelength edge, the other (1557.484 nm) closer to the center of the lasing spectrum. The short wavelength line has lower power, higher RIN, and larger optical linewidth, all of which likely contribute to the raised noise floor. Figure 5(b) shows the measured eye diagram for the channel at 1557.484 nm after B2B and 25-km SSMF transmission. Open and clear eyes can be demonstrated and the aggregate data transmission capacity achieved of 34.224 GHz QD-MLL is 5.376 Tbit/s (PAM-4 48 × 28 GBaud PDM).

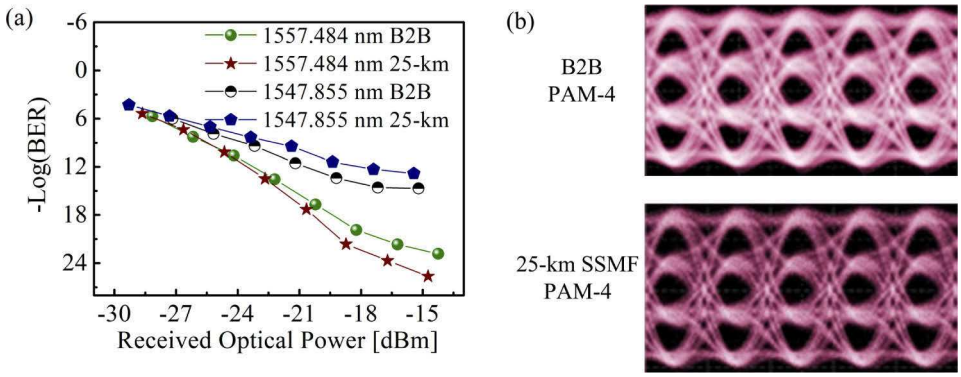

Fig. 5. (a) BER evaluation versus received optical power for B2B and after 25-km of SSMF transmission using the comb lines located at 1557.484 nm and 1547.855 nm; and (b) corresponding eye diagram for selected channel at 1557.484 nm after B2B and 25-km of SSMF transmission.

4. Conclusion

We have developed a 34.224 GHz InAs/InP quantum dash mode-locked laser (QD-MLL) with 48 individual channels. The QD-MLL shows excellent intensity and phase noise performance. The integrated RIN value for the 48 filtered individual channels are approximately -128 dB/Hz and the average optical linewidth is 1.55 MHz. By employing 48 wavelength channels as optical carriers, 5.376 Tbit/s PAM-4 aggregate data transmission capacity is demonstrated with the base modulation rate of 28 GBaud over 25-km standard single-mode fiber. To the best of our knowledge, this represents the first demonstration of QD-MLL acting as error-free operation at an aggregate data transmission capacity of 5.376 Tbit/s for some channels. These achievements may be a significant step towards low-cost, high wavelength channel count light source for large-scale optical networking systems.

Acknowledgments

The authors would like to acknowledge the support of National Research Council Canada's high throughput and secure networks (HTSN) research program.

Optics EXPRESS

Disclosures

The authors declare no conflicts of interest.

References

1. H. Hu, F. Da Ros, M. Pu, F. Ye, K. Ingerslev, E. P. da Silva, M. Nooruzzaman, Y. Amma, Y. Sasaki, and T. Mizuno, "Single-source chip-based frequency comb enabling extreme parallel data transmission," Nat. Photonics **12**(8), 469–473 (2018).
2. Q. Cheng, M. Bahadori, M. Glick, S. Rumley, and K. Bergman, "Recent advances in optical technologies for data centers: a review," Optica **5**(11), 1354–1370 (2018).
3. 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**(1), 211–263 (2018).
4. V. Vujicic, A. P. Anthur, A. Saljoghei, V. Panapakkam, R. Zhou, Q. Gaimard, K. Merghem, F. Lelarge, A. Ramdane, and L. P. Barry, "Mitigation of relative intensity noise of quantum dash mode-locked lasers for PAM4 based optical interconnects using encoding techniques," Opt. Express **25**(1), 20–29 (2017).
5. V. Vujicic, C. Calo, R. Watts, F. Lelarge, C. Browning, K. Merghem, A. Martinez, A. Ramdane, and L. P. Barry, "Quantum dash mode-locked lasers for data centre applications," IEEE J. Sel. Top. Quantum Electron. **21**(6), 53–60 (2015).
6. M. I. Olmedo, T. Zuo, J. B. Jensen, Q. Zhong, X. Xu, S. Popov, and I. T. Monroy, "Multiband carrierless amplitude phase modulation for high capacity optical data links," J. Lightwave Technol. **32**(4), 798–804 (2014).
7. Z. Lu, "Quantum-dot coherent comb lasers for terabit optical networking systems," Proc. SPIE **10921**, 109210N (2019).
8. 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**(2), 128–134 (2019).
9. E. U. Rafailov, M. A. Cataluna, and W. Sibbett, "Mode-locked quantum-dot lasers," Nat. Photonics **1**(7), 395–401 (2007).
10. Y. Mao, J. Liu, Z. Lu, C. Song, and P. J. Poole, "Ultra-low timing jitter of quantum dash semiconductor comb lasers with self-injection feedback locking," IEEE J. Sel. Top. Quantum Electron. **25**(6), 1900607 (2019).
11. P. Marin-Palomo, J. N. Kemal, P. Trocha, S. Wolf, K. Merghem, F. Lelarge, A. Ramdane, W. Freude, S. Randel, and C. Koos, "Comb-based WDM transmission at 10 Tbit/s using a DC-driven quantum-dash mode-locked laser diode," Opt. Express **27**(22), 31110–31129 (2019).
12. J. N. Kemal, P. Marin-Palomo, V. Panapakkam, P. Trocha, S. Wolf, K. Merghem, F. Lelarge, A. Ramdane, S. Randel, W. Freude, and C. Koos, "Coherent WDM transmission using quantum-dash mode-locked laser diodes as multi-wavelength source and local oscillator," Opt. Express **27**(22), 31164–31175 (2019).
13. J. Wang and Y. Long, "On-chip silicon photonic signaling and processing: a review," Sci. Bull. **63**(19), 1267–1310 (2018).
14. Z. Wang, A. Abbasi, U. Dave, A. De Groote, S. Kumari, B. Kunert, C. Merckling, M. Pantouvaki, Y. Shi, and B. Tian, "Novel light source integration approaches for silicon photonics," Laser Photonics Rev. **11**(4), 1700063 (2017).
15. F. Lelarge, B. Dagens, J. Renaudier, R. Brenot, A. Accard, F. van Dijk, D. Make, O. Le Gouezigou, J.-G. Provost, and F. Poingt, "Recent advances on InAs/InP quantum dash based semiconductor lasers and optical amplifiers operating at 1.55 μm," IEEE J. Sel. Top. Quantum Electron. **13**(1), 111–124 (2007).
16. Z. Lu, J. Liu, P. Poole, C. Song, and S. Chang, "Ultra-narrow linewidth quantum dot coherent comb lasers with self-injection feedback locking," Opt. Express **26**(9), 11909–11914 (2018).
17. Z. Lu, J. Liu, C. Song, J. Weber, Y. Mao, S. Chang, H. Ding, P. Poole, P. Barrios, and D. Poitras, "High performance InAs/InP quantum dot 34.462-GHz C-band coherent comb laser module," Opt. Express **26**(2), 2160–2167 (2018).
18. Z. Lu, J. Liu, S. Raymond, P. Poole, P. Barrios, and D. Poitras, "312-fs pulse generation from a passive C-band InAs/InP quantum dot mode-locked laser," Opt. Express **16**(14), 10835–10840 (2008).
19. P. Poole, K. Kaminska, P. Barrios, Z. Lu, and J. Liu, "Growth of InAs/InP-based quantum dots for 1.55 μm laser applications," J. Cryst. Growth **311**(6), 1482–1486 (2009).
20. D. Inoue, D. Jung, J. Norman, Y. Wan, N. Nishiyama, S. Arai, A. C. Gossard, and J. E. Bowers, "Directly modulated 1.3 μm quantum dot lasers epitaxially grown on silicon," Opt. Express **26**(6), 7022–7033 (2018).
21. K. Zhong, X. Zhou, Y. Gao, W. Chen, J. Man, L. Zeng, A. P. T. Lau, and C. Lu, "140-Gb/s 20-km transmission of PAM-4 signal at 1.3 μm for short reach communications," IEEE Photonics Technol. Lett. **27**(16), 1757–1760 (2015).
22. M. J. Heck, E. J. Salumbides, A. Renault, E. A. Bente, Y.-S. Oei, M. K. Smit, R. van Veldhoven, R. Nötzel, K. S. Eikema, and W. Ubachs, "Analysis of hybrid mode-locking of two-section quantum dot lasers operating at 1.5 μm," Opt. Express **17**(20), 18063–18075 (2009).

167.37.63.9 {ts '2020-07-07 15:21:22'}