A passively mode-locked quantum dot laser with 10.8 Tbit/s transmission over 100-km SSMF

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Abstract: We demonstrate 10.8 Tbit/s (16-QAM 48×28 GBaud PDM) coherent data transmission over 100-km of standard single mode fiber using an InAs/InP quantum dot mode-locked laser with a channel spacing of 34.2 GHz.
OCIS codes: (230.5590) Quantum well, wire and dot devices; (140.4050) Mode-locked lasers; (060.1660) Coherent communications

1. Introduction

The high demand for ultrahigh-speed optical networks results in intensive efforts in the development of new advanced photonics components towards the realization of greater than 1 Tbit/s transmission capacity [1, 2]. The use of wavelength division multiplexing (WDM) and advanced modulation formats [2] is becoming more and more attractive to alleviate transmission bottlenecks in data centers and long-haul networks. 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 [3] 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 [4]. Moreover, they offer reduced spontaneous emission rates and low threshold current densities which leads to reduced intrinsic noise [2-4].

Various demonstrations have been carried out to show the potential of QD MLLs for Tbit/s transmission [4-7]. In recent years we have reported several InAs/InP QD MLLs operating in the *C*-band [7-9]. In this paper, we have developed an InAs/InP QD MLL with the channel spacing of 34.2 GHz and have investigated its optical intensity and phase noise performance. Then using this laser we have successfully demonstrated 10.8 Tbit/s (16-QAM 48×28 GBaud PDM) coherent data transmission capacity both for back-to-back (B2B) and over 100-km of standard single-mode fiber (SSMF) configuration.

2. InAs/InP QD laser and Experimental set-up

The InAs/InP QD material was grown by chemical beam epitaxy (CBE) on exactly *n*-type InP substrates [10]. A 355 nm thick InGaAsP waveguide core contained five stacked layers of InAs QDs as the gain medium, surrounded by *n*- and *p*- type InP cladding layers. Single lateral mode ridge waveguide QD MLLs were fabricated with a stripe width of 2.0 μm and a Fabry-Perot (F-P) laser cavity length of 1227 μm. The laser was mounted on a copper block, 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 noise was recorded with an Agilent N4371A relative intensity noise measurement system and an OE4000 automated laser linewidth/phase noise measurement system (OEWaves Inc.).

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 transmitter (SHF Communication Technologies AG, Model SHF 46215B DP-QAM) for data modulation. A modulated 28 GBaud 16-QAM 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 100-km of SSMF. Finally, after optimizing the power and signal using EDFA and OBPF, the received signal was processed by a built-in 65 GHz optical detector (Keysight Technologies, Model 86116C) and an integrated optical modulation analyzer (Keysight Technologies, Model N4392A).

3. Results and Discussion

Fig. 1(a) shows the lasing optical spectrum, which exhibits the center wavelength is 1554.22 nm and the 6-dB comb bandwidth is 13.05 nm, providing 48 channels with an optical signal-to-noise ratio (OSNR) of more than 40 dB. RF performance is presented in Fig. 1(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 obtained RF linewidth with a Lorentzian fit. The 3 dB linewidth is 1.688 kHz, which is comparable to advanced high-speed semiconductor MLLs [4].

Fig 2(a).shows the relative intensity noise (RIN) spectrum for both the whole *C*-band spectrum and one filtered single channel without EDFA. We achieve an integrated average RIN value less than -159 dB/Hz for the whole laser in the frequency range from 10 MHz to 10 GHz, with the upper bound set by the instrument limited RIN measurement floor. Such a low RIN value is attributed to the characteristics of QD material inside the laser cavity. For the filtered single channel at 1552.924 nm, the integrated average RIN value increases to about -130.2 dB/Hz due to mode partition noise. The integrated RIN value for the other 47 filtered individual channels are also approximately -129 dB/Hz. Fig. 2(b) shows the optical linewidth of each of the filtered individual channels from 1551.824 nm to 1556.816 nm at 330 mA and 17°C. The average optical linewidth of each mode is around 1.4 MHz, measured by the delayed self-heterodyne method. 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.

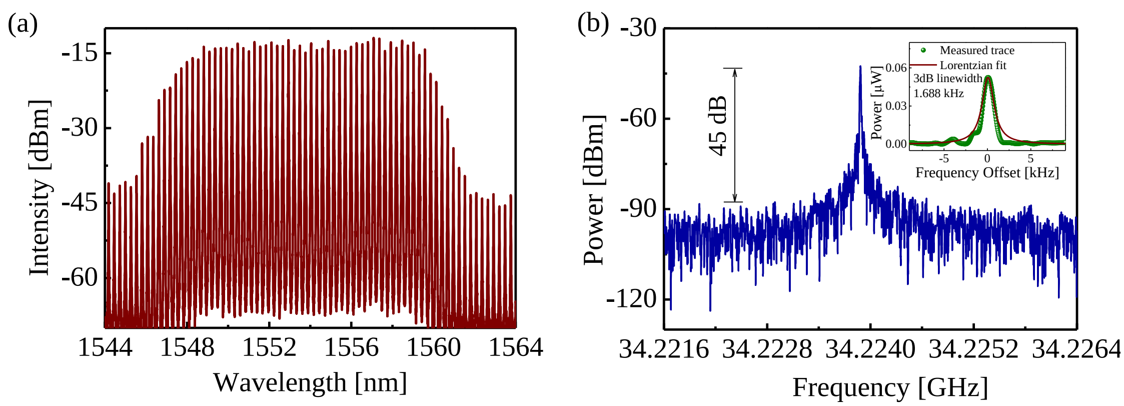

FIG. 1 (a) Optical output spectrum of a QD MLL with a ridge width of 2 μm and cavity length of 1227 μm, measured at 330 mA and 17°C; (b)RF beating frequency of 34.224 GHz between any two adjacent channels (RBW:5 kHz). The inset is the narrow span RF peak with Lorentzian fit (RBW:1 kHz).

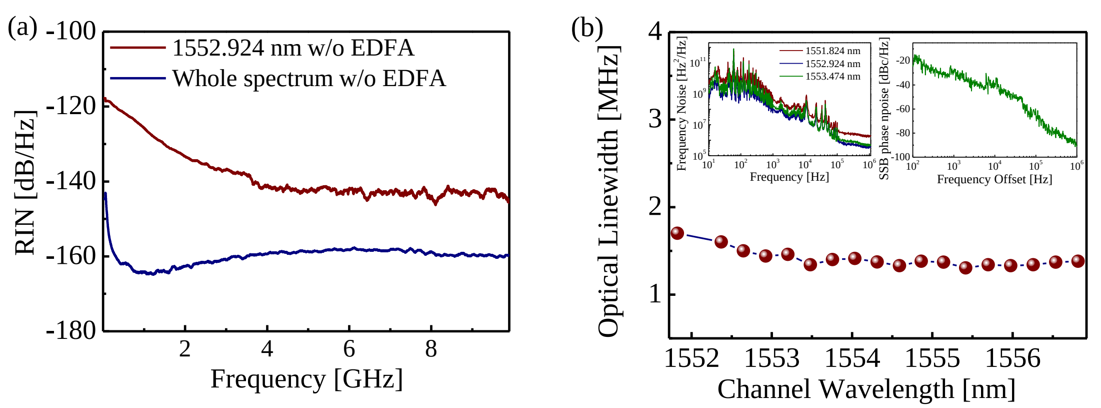

FIG. 2 (a) RIN of the QD MLL and of a single channel after optical filtering; and (b) Optical linewidth of the filtered individual channels from 1551.824 nm to 1556.816 nm at 330 mA and 17°C. The left inset is a comparison of the frequency noise spectra from three filtered wavelength channels of 1551.824 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.

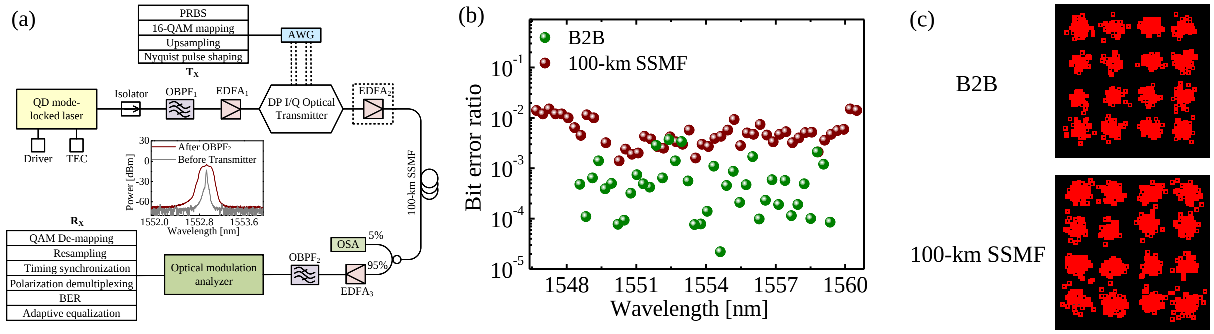

FIG. 3 (a) 16-QAM data transmission setup with the DP I/Q optical transmitter (T_X) and the receiver (R_X). $EDFA_2$ is only used for 100-km SSMF transmission. The inset shows the OSA spectra of one filtered channel at 1552.924 nm, include after $OBPF_2$ and before transmitter, (b) Measured BER and (c) measured constellation diagram for selected channels at 1552.924 nm for B2B and 100 km SSMF transmission.

Fig. 3(a) shows the experimental setup for the 16-QAM data transmission. At the dual polarization (DP) I/Q optical transmitter side (T_X), a 28 GBaud 16-QAM signal is created using an AWG generating a pseudo-random bit sequence (PRBS) with a pattern length of 2^{15}-1 bits as a symbol rate of 28 Gbit/s non-return to zero (NRZ) on four channels. A root-raised-cosine (RRC) filter is applied with the roll-factor of 0.35 for Nyquist pulse filtering. At the receiver side (R_X), the modulated signal is firstly amplified by an $EDFA_3$, and an optical bandpass filter $OBPF_2$ is used to filter out the ASE from the EDFA. A matched RRC filter is executed to mitigate the effects of white noise and clock recovery is carried out to compensate for any sampling phase and frequency offset that may exist between the transmitter and receiver clocks. Finally, the output 16-QAM signal is decoded for bit error ratio (BER) measurements. The inset shows the optical spectra of one filtered channel at 1552.924 nm, at the output before modulation and that after spectral broadening and 16-QAM modulation. The modulated optical signal is transmitted both for B2B configuration and over 100-km SSMF, respectively. Fig. 3(b) shows the transmission results. All selected channels exhibit BERs performance below the 7% HD-FEC limit (BER=4×10^{-3}) after B2B transmission and 20% SD-FEC limit (BER=1.6×10^{-2}) after 100-km SSMF (chromatic dispersion of 17 ps/nm/km). Fig. 3(c) shows the measured constellation diagram for the channel at 1552.924 nm after B2B and 100-km SSMF transmission. The aggregate raw capacity achieved of 34.2 GHz QD MLL is 10.8 Tbit/s (16-QAM 48×28 GBaud PDM).

4. Conclusion

We have demonstrated a 34.2 GHz quantum dot mode-locked laser (QD-MLL). The QD-MLL shows excellent intensity and phase noise performance. By employing 48 wavelength channels as optical carriers, a system-level 10.8 Tbit/s 16-QAM signal detection is demonstrated with the transmission at 28 GBaud both for back-to-back and over 100-km standard single-mode fiber configuration.

5. References

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