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Quantum dash multi-wavelength lasers for Tbit/s coherent communications and 5G wireless networks

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Abstract

We report on the design, growth, fabrication, and performance of InAs/InP quantum dash (QD) multi-wavelength lasers (MWLs) developed by the National Research Council (NRC) Canada. The key technical specifications investigated include optical and RF beating spectra, relative intensity noise (RIN), and optical phase noise of each individual wavelength channel. Data bandwidth transmission capacity of 5.376 Tbit/s and 10.8 Tbit/s respectively in the PAM-4 and 16-QAM modulation formats are demonstrated using only a single C-band QD 34.2-GHz MWL chip. We have also developed a monolithic InAs/InP QD dual-wavelength (DW) DFB laser as a compact optical beat source to generate millimeter-wave (MMW) signals. Due to the common cavity, highly coherent and correlated optical modes with optical linewidth as low as 15.83 kHz, spectrally pure MMW signals around 46.8 GHz with a linewidth down to 26.1 kHz were experimentally demonstrated. By using this QD DW-DFB laser, a one GBaud (2 Gbps) MMW over-fiber transmission link is demonstrated with PAM-4 signals. The results show that the demonstrated device is suitable for high speed high capacity MMW fiber-wireless integrated fronthaul of 5G networks.

Keywords: Optical communications, Multi-wavelength lasers, Coherent terabit/s networking systems, Millimeter wave, Radio over fiber, Data center networks, Coherent optical networks, Quantum dash, Quantum dot semiconductor mode-locked lasers, Integrated optics devices

Introduction

Over the past years many experiments have demonstrated the huge potential of using optical multi-wavelength lasers (MWLs) for data transmission at terabit rates [1–3]. Quantum dot and dash (QD) semiconductor multi-wavelength lasers (MWLs) are promising light sources for Terabit/s dense wavelength division multiplexing (WDM) optical coherent networks, optical signal processing and millimeter wave (MMW) generation with many unique advantages over quantum well (QW) and bulk semiconductor materials. These advantages include an inherently inhomogeneously broadened gain spectrum [4], ultrafast carrier dynamics [5], stable optical pulse trains at high repetition rates [4], narrow pulse widths [6], and low amplified spontaneous emission (ASE) noise level [7–9]. By replacing many separate lasers for each wavelength channel with only a single QD based laser chip [10–15] helps to reduce cost, power consumption, and packaging problems. Other advantages include compact size, simple fabrication, and the ability for hybrid integration with silicon substrates [16]. In recent years we have successfully developed InAs/InP QD MWLs with repetition rates from 10 GHz to 437 GHz and a total output power up to 50 mW per facet at room temperature [17–19]. In this paper we give an overview of the performance of the QD MWLs and their

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applications in Terabit/s optical communication links and 5G wireless networks.

QD materials and QD MWLs for Tbit/s networks

The InAs/InP MWL QD material was grown by chemical beam epitaxy (CBE) on exactly (001)-oriented *n*-type InP substrates [20]. 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. Single lateral mode ridge waveguide Fabry-Perot (*F-P*) QD-MWLs were fabricated with a stripe width of 2.0 μm using standard photolithography and combination of dry-, wet-etching and contact metallization techniques. Figure 1a shows a scanning electron microscope (SEM) cross-section image with the corresponding schematic shown in Fig. 1b.

The performance of the lasers was characterized using an Optical Spectrum Analyzer (OSA) (Anritsu MS9740A), Relative Intensity Noise Measurement System (Agilent N4371A), a 50 GHz PXA Signal Analyzer (Keysight N9030A), a Finisar Ultra-Fast 100 GHz Photodetector XPDV4120R, an Optical Autocorrelator (Femtochrome Research Inc. FR-103HS), a Delayed Self-Heterodyne Interferometer (Advantest Q7332 & R3361A),an OE4000 Automated Laser Linewidth Measurement System (OEWaves Inc.), Santec Optical Bandpass Filter (OBPF) OTF-350, Arbitrary Waveform Generator (AWG) (Keysight M8195A), built-in 65 GHz Optical Detector (Keysight 86116C), Keysight Optical Modulation Analyzer N4392A, 86100D Infiniium DCA-X Wide-Bandwidth Oscilloscope, Intensity Modulator (Thorlab LN05–40-S-A-A-NS), SHF 46215B DP-QAM Transmitter with 10001B small main frame, RF Amplifier and Bias Controller (Anritsu AH34152A), Erbium-Doped Fiber Amplifiers (EDFAs) and other photonic components.

Figure 2a shows a schematic of the experimental setup to characterize the performance of the QD MWL Fig. 2b shows the optical spectrum of a QD MWL with an active length of 1227 μm, which gives a frequency spacing of 34.224 GHz at 350 mA and 18 °C with a single facet output power of 40 mW. The center wavelength is 1554.22 nm and the 6 dB bandwidth is 12.96 nm, providing 48 channels with an optical signal-to-noise ratio (OSNR) of more than 40 dB. From the *L-I-V* curves we obtain a lasing threshold current of 46 mA with a slope efficiency of 0.133 mW/mA and a series resistance of 1.52 Ohm. The RF beating signal is presented in Fig. 2c showing a sharp fundamental RF beating frequency at 34.224 GHz and a signal to noise floor ratio (SNR) of larger than 45 dB. Figure 2d shows the RF linewidth with a Lorentzian fit. The 3 dB linewidth is 1.688 kHz, and such an extremely narrow linewidth leads to ultra-low pulse-to-pulse time jitter value of 2.59 fs [21] and phase noise [22].

Figure 3a shows the RIN spectra for both the whole lasing spectrum and three filtered channels of 1557.484 nm, 1548.932 nm and 1558.596 nm. We achieve an integrated average RIN value less than − 160.5 dB/Hz for the whole lasing spectrum, with the upper bound set by the instrument limited RIN measurement floor. For the three filtered channels the integrated average RIN value increases to about − 130.5 dB/Hz. The integrated RIN values for all 48 filtered individual channels are approximately − 130 dB/Hz in the frequency range from 10 MHz to 10 GHz. Figure 3b is a comparison of the frequency noise spectra from three filtered wavelength channels at 1551.824 nm, 1552.924 nm and 1553.474 nm. Figure 3c 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 good noise performance is believed to benefit from the low amplified spontaneous emission (ASE)

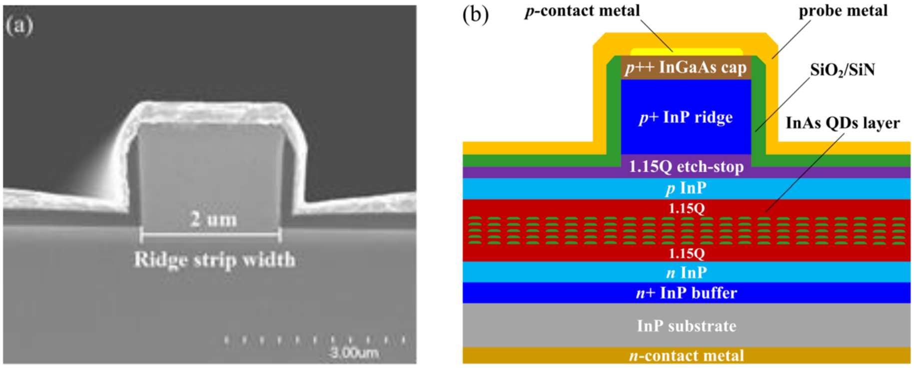

Fig. 1 **a** Cross-sectional SEM image showing the facet of a fabricated F-P InAs/InP QD laser; **b** Schematic cross-sectional diagram of a shallow-etched ridge-waveguide InAs/InP QD MWL

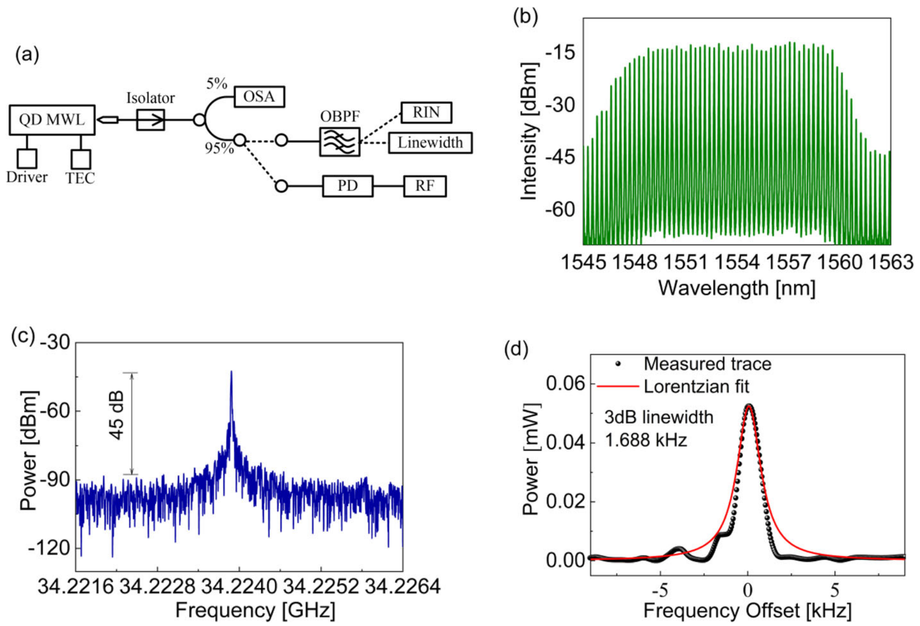

Fig. 2 a Schematic of the experimental setup for the performance of the QD MWL, including OSA, OBPF, the RIN tested by the relative intensity noise measurement system, the optical linewidth tested by the OE4000 automated laser linewidth measurement system and the RF beating signals tested by the PXA signal analyzer with the photodetector (PD). **b** Optical spectrum of a QD MWL with a cavity length of 1227 μm, measured at 350 mA and 18 °C (Noise floor: − 60 dBm and resolution bandwidth (RBW): 0.01 nm); **c** RF beating frequency of 34.224 GHz between any two adjacent channels (RBW: 5 kHz). **d** The narrow span RF peak with Lorentzian fit (RBW: 1 kHz)

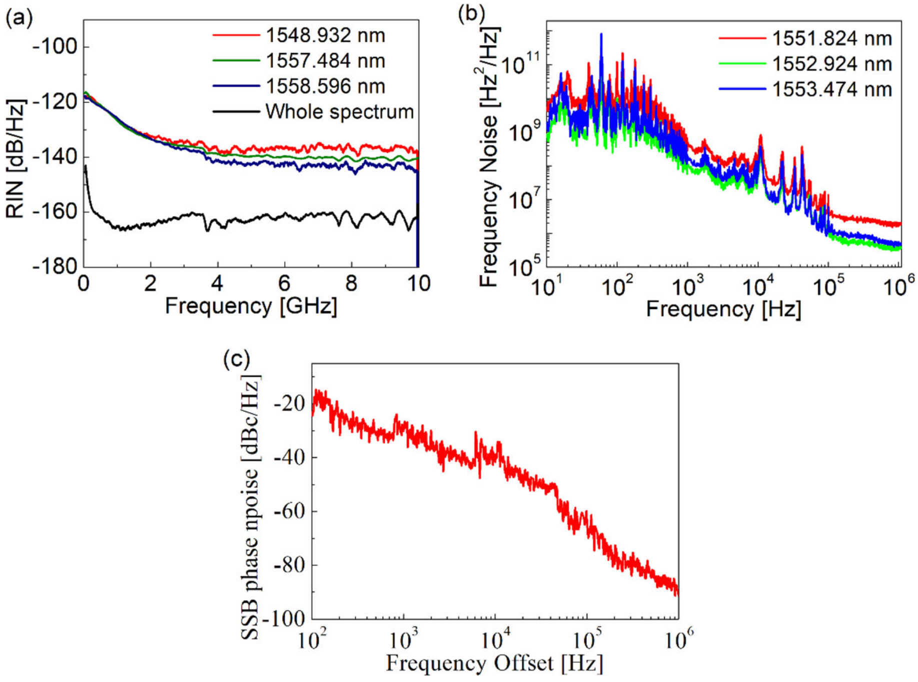

Fig. 3 a Measured RIN for the whole laser and three filtered channels in the frequency range from 10 MHz to 10 GHz. **b** Optical linewidth of the frequency noise spectra from three filtered channels of 1551.824 nm, 1552.924 nm and 1553.474 nm. **c** The single-sideband (SSB) phase noise of the RF beating signal noise and low confinement factor properties of the QD MWL material [23, 24].

To demonstrate the performance of these lasers in a Tbit/s system we have used both PAM-4 and 16-quadrature amplitude modulation (16-QAM) modulation schemes. Figure 4a shows the experimental setup for PAM-4 and 16-QAM data transmission system where the optical modulation is performed by a dual polarization QAM transmitter. A PAM-4 signal is created using the arbitrary waveform generator for a non-return to zero (NRZ) pseudo-random bit sequence (PRBS) with a pattern length of $2^{15}-1$ bits at a symbol rate of 28 GBaud on two uncorrelated channels (*IY* and *IX*). Figure 4b shows the bit error rate (BER) as a function of received power for back-to-back (B2B) and after 25 km of standard single mode fiber (SSMF) transmission (chromatic dispersion of 17 ps/nm/km) using a single filtered wavelength mode at 1547.855 nm (one of the 48 channels) in the 34.2 GHz laser. Without chromatic dispersion compensation, a clear eye diagram cannot be attained. The inset shows the measured eye diagram after 25 km SSMF showing open eyes. The potential aggregate transmission capacity for the 48 channels available is 5.376 Tbit/s (PAM-4 48 × 28 GBaud PDM) over 25 km of a SSMF transmission [8]. Figure 4c shows a 16-QAM constellation diagram at a symbol rate of 28 GBaud obtained from a filtered single laser mode at 1552.92 nm for the 34.2 GHz laser. We obtained 16-QAM results at the base rate of 28 GBaud over 48 individual channels, which corresponds to an aggregate transmission capacity of 10.8 Tbit/s (16-QAM 48 × 28 GBaud PDM) B2B and 100 km SSMF [9].

QD DW DFB lasers for 5G wireless networks

For the dual wavelength laser used for millimeter wave generation a buried heterostructure approach was taken for its fabrication. The device was implemented in a *p-n* blocked buried heterostructure (BH) distributed feedback (DFB) laser with a novel synthesized aperiodic non-uniform diffraction grating layer placed below the InAs/InP QD active layer, which provided the distributed feedback such that two longitudinal modes lased simultaneously [25]. Figure 5a shows the typical *L-I* characteristics of the device. Lasing starts at a threshold current

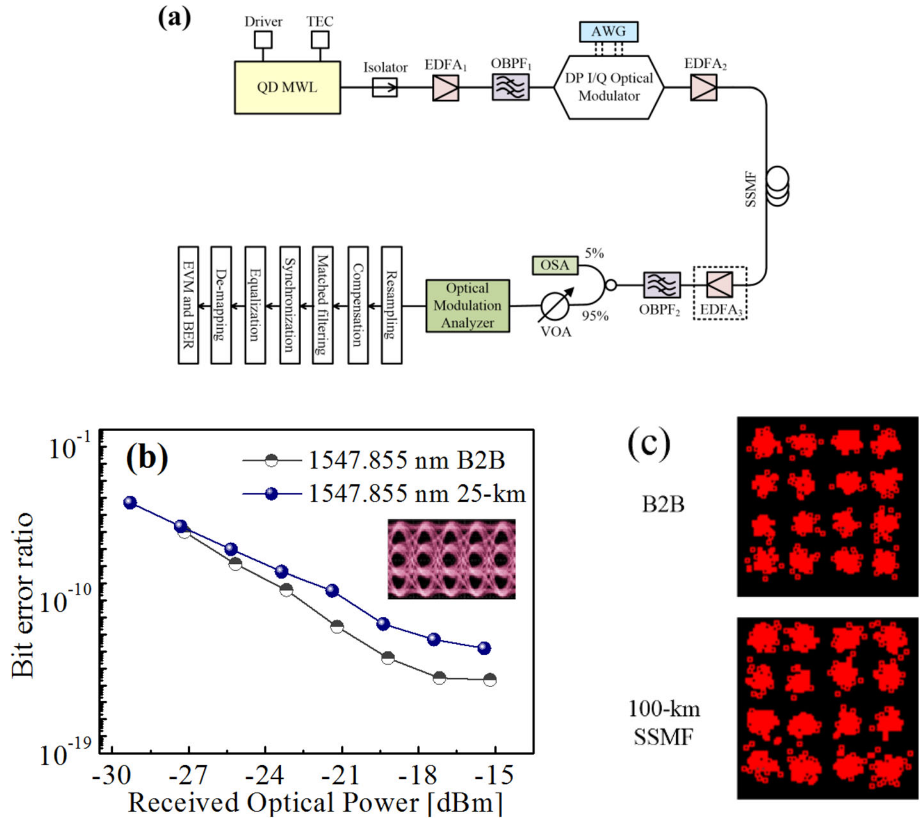

Fig. 4 **a** A schematic of PAM-4 and QAM data format system. **b** Measured BER versus received power for PAM-4 B2B and after 25 km of SSMF transmission using a 1547.855 nm comb line of the 34.2 GHz QD MWL. The inset shows corresponding eye diagram for 25 km of SSMF transmission (chromatic dispersion of 17 ps/nm/km). **c** A constellation eye diagram obtained from filtered channel of 1552.92 nm for the 34.2 GHz QD MWL in the double polarization 16-QAM data format at 28 GBaud for B2B and 100 km SSMF transmission (chromatic dispersion of 17 ps/nm/km)

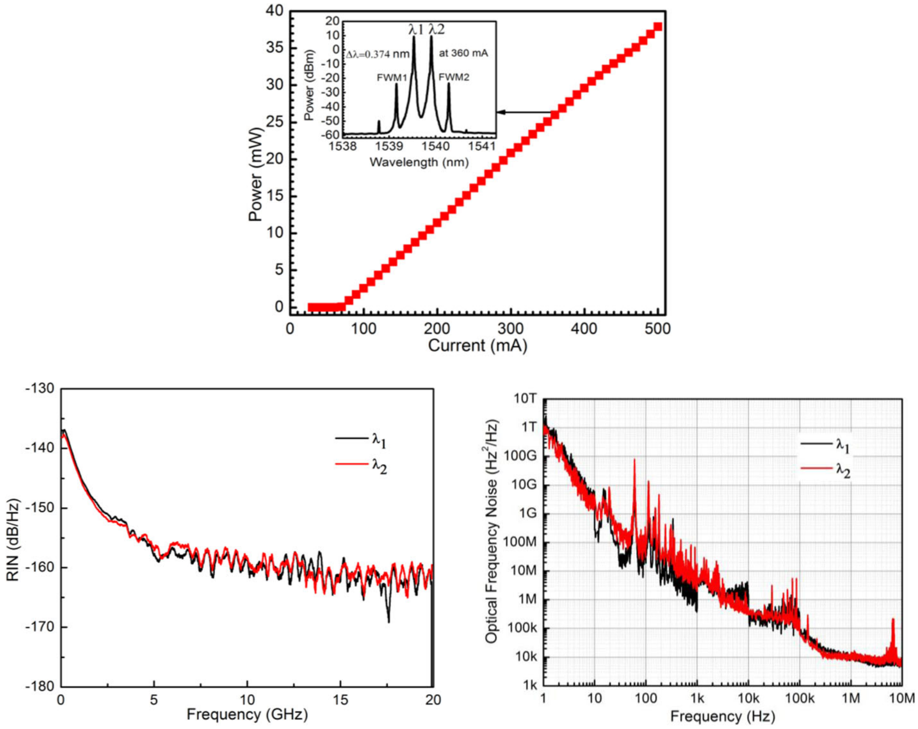

Fig. 5 Measured (**a**) *L-I* characteristics of the QD DW-DFB laser (inset shows the optical spectrum at 360 mA). **b** RIN spectra and **c** optical frequency noise spectra at a bias current of 360 mA

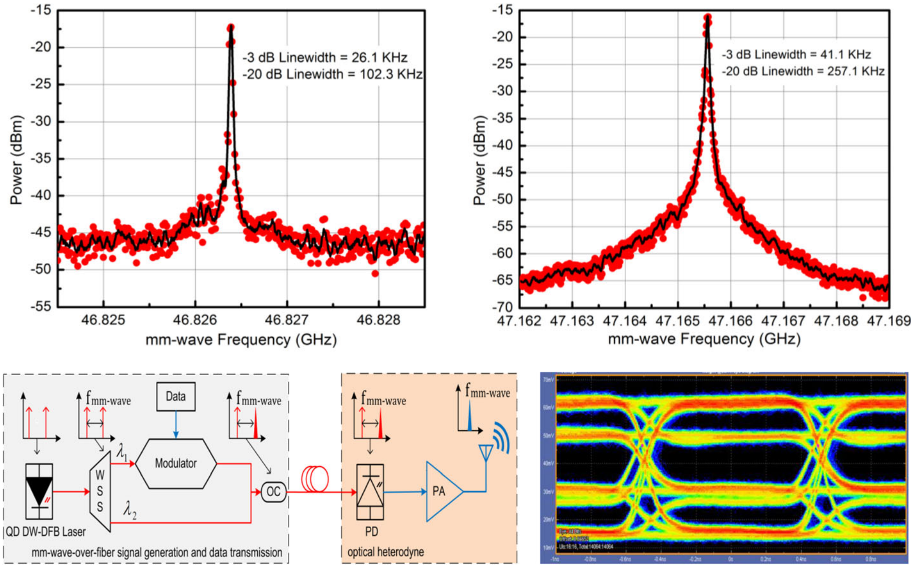

Fig. 6 Measured spectra (in red) with smoothing version of the results (in black) for − 3 dB and − 20 dB linewidth measurements of **a** 46.82639 GHz MMW signal at 300 mA (resolution bandwidth (RBW) = 51 kHz, video bandwidth (VBW) = 1 kHz) and **b** 47.16556 GHz MMW signal at 360 mA (RBW = 51 kKHz, VBW = 510 Hz). **c** Photonic mm-wave-over-fiber signal generation and data transmission using optical heterodyne and **d** Received PAM-4 signals' eye diagram

of around 70 mA and the device shows stable linear behaviour in terms of output power as a function of injection current. Although the device exhibits stable dual-wavelength lasing in a large range of injection currents, the intensity of the two optical modes becomes equal around 360 mA with a wavelength spacing of 0.374 nm as depicted in the inset of Fig. 5a. Figure 5b and c show the RIN and phase noise measured experimentally for the two dominant optical modes. At 360 mA, optical linewidths of 25.9 kHz and 29.4 kHz were measured for the two optical modes at $\lambda_1 = 1539.522$ nm and $\lambda_2 = 1539.896$ nm, respectively. Average RIN was measured as − 150.8 dB/Hz for λ_1 and − 151.4 dB/Hz for λ_2 over the frequency range from 10 MHz to 20 GHz.

Figure 6a and b show typical spectra of the corresponding beat note signals of 46.82639 GHz and 47.16556 GHz, respectively, which were generated at a bias current of 300 mA and 360 mA. For accurate measurement of the MMW spectral linewidths, the curves in Fig. 6a and b were smoothed (the black curves show smoothed results). The measured − 3 dB and − 20 dB spectral linewidths of the MMW signal at 46.82639 GHz are 26.1 kHz and 102.3 kHz, respectively. Similarly, for the MMW signal at 47.16556 GHz, the − 3 dB and − 20 dB spectral linewidths were 41.1 kHz and 257.1 kHz, respectively.

Figure 6c and d show an MMW over-fiber transmission link, λ_2 of the QD DW-DFB laser was modulated using a 40 GHz Mach-Zehnder intensity modulator (MZ-IM) with one GBaud (2 Gbps) PAM-4 signals generated through the arbitrary waveform generator and λ_1 was used as beat note signal for heterodyne MMW carrier generation. A clear eye diagram of PAM-4 signals of one GBaud transmission bandwidth along with transmitted / received signals were measured using Tektronix digital phosphor real-time oscilloscope. These results indicate the promising applications of the demonstrated QD DW-DFB laser as a compact mm-wave optical beat source in heterodyne mm-wave communication systems of 5G and beyond wireless networks.

Conclusions

We have demonstrated a 34.2 GHz *C*-band QD multi-wavelength laser (MWL) which provides 48 individual channels with an OSNR of more than 40 dB. This QD MWL has shown ultra-low intensity and phase noise performance. The integrated RIN value for all 48 filtered individual channels are approximately − 130 dB/Hz and the average optical linewidth is 1.5 MHz. By employing 48 wavelength channels as optical carriers, 5.4 Tbit/s PAM-4 aggregate data transmission capacity is demonstrated with the base modulation rate of 28 GBaud over 25 km SSMF. We have also used those 48 channels from this 34.2 GHz QD MWL as optical carriers, a system-level 10.8 Tbit/s 16-QAM signal detection is demonstrated with the transmission at 28 GBaud both for B2B and over 100 km SSMF configuration. The above achievements are a significant step towards a low-cost, chip-scale, high wavelength channel count laser source for large-scale optical networking systems with tens Tbit/s data transmission capabilities.

We also have developed and experimentally demonstrated a novel monolithic InAs/InP QD DW-DFB laser operating in the *C*-band for MMW signals generation. The device simultaneously generates two highly coherent optical modes with spectral linewidths as narrow as 15.83 kHz and average RIN down to − 158.3 dB/Hz. Optical heterodyne beating of these two modes results in MMW signals between 46 and 48 GHz with extremely narrow linewidth, down to 26 kHz. Using this laser and optical heterodyning, we experimentally demonstrate a one GBaud four-level pulse amplitude modulation (PAM-4) photonic MMW system at 47.2 GHz. The results show that the demonstrated device is suitable for MMW applications, particularly Radar and high capacity MMW fiber-wireless integrated fronthaul for 5G and beyond.

Abbreviations

QD: Quantum dot and dash; BH DFB: Buried heterostructure distributed feedback; MWLs: Multi-wavelength lasers; EDFAs: Erbium-doped fiber amplifiers; RIN: Relative intensity noise; ASE: Amplified spontaneous emission; OSNR: Optical signal-to-noise ratio; NRZ: Non-return to zero; WDM: Wavelength division multiplexing; PRBS: Pseudo-random bit sequence; SSB: Single-sideband; RBW: Resolution bandwidth; VBW: Video bandwidth; B2B: Back-to-back; SSMF: Standard single mode fiber; PAM-4: Four-level pulse amplitude modulation; 16-QAM: 16-quadrature amplitude modulation; BER: Bit error rate; WSS: Wavelength selective switch; OC: Optical coupler; PD: Photodetector; PA: Power amplifier

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Authors' contributions

All authors contribute to the designed, discussion and preparation of the manuscript. The authors read and approved the final manuscript.

Availability of data and materials

Please contact authors for data requests.

Declarations

Competing interests

The authors declare that they have no competing interests.

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