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# High performance InAs/InP quantum dot 34.462-GHz C-band coherent comb laser module

**Z. G. Lu,[1,*] J. R. Liu,[1] C. Y. Song,[1] J. Weber,[1] Y. Mao,[1] S. D. Chang,[1] H. P. Ding,[1] P. J. Poole,[1] P. J. Barrios,[1] D. Poitras,[1] S. Janz,[1] and M. O'Sullivan[2]**

[1]*Advanced Electronics and Photonics Research Centre, National Research Council, Ottawa, ON, Canada*
[2]*Ciena, Ottawa, ON, Canada*
**Zhenguo.Lu@NRC-CNRC.GC.CA*

**Abstract:** We have developed an InAs/InP quantum dot (QD) C-band coherent comb laser (CCL) module with actively stabilized absolute wavelength and power, and channel spacing of 34.462 GHz with ± 100 ppm accuracy. The total output power is up to 46 mW. The integrated average relative intensity noise (RIN) values of the lasing spectrum and a filtered single channel at 1540.19 nm were –165.6 dB/Hz and –130.3 dB/Hz respectively in the frequency range from 10 MHz to 10 GHz. The optical linewidth of the 45 filtered individual channels between 1531.77 nm to 1543.77 nm ranged from 850 kHz to 2.16 MHz. We have also analyzed the noise behaviors of each individual channel.



**OCIS codes:** (060.4510) Optical communications; (230.5590) Quantum-well, -wire and -dot devices; (140.5960) Semiconductor lasers; (140.4050) Mode-locked lasers; (130.3120) Integrated optics devices.

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## 1. Introduction

The telecommunications industry is striving to improve and develop new network architectures, transmission formats, and photonic components to keep up with the exponential growth of global internet data traffic [1]. The two most notable advances in transmission have been wavelength division multiplexing (WDM) and coherent communications. Both formats continue to evolve and are being combined to create even more advanced networks. Semiconductor lasers are the light source at the heart of these systems, and must meet an ever more demanding and diverse set of technical specifications. Most recently, there has been a significant amount of interest in optical comb lasers as monolithic source of multiple wavelength channels for WDM, dense-WDM (DWDM), super-channel and flex-grid architectures. Such comb lasers solve the obvious cost and packaging problems by replacing many separate lasers for each channel by a single laser chip. Comb lasers have now been used to demonstrate optical systems with net data rates exceeding Terabit/s transmission and very high spectral efficiency [2–6]. Many techniques have been used to generate multi-wavelength combs including RF modulation [4], spatial mode beating [7], spectral broadening in nonlinear fiber [8], and high-Q microresonators filters [9]. However, these techniques either require complex setups, high pump powers with finely tuned operating parameters, or they provide only a limited number of spectral carriers. For practical systems, a compact, low-cost, energy-efficient semiconductor comb laser is desired [10-11]. Furthermore, some of the new transmission schemes also require that the wavelength channels are mutually coherent, or locked together in phase.

In recent years we have reported on InAs/InP quantum dot (QD) multi-wavelength lasers emitting light over a large wavelength range covering the C- and L-bands [12–17]. In addition to emitting a stable comb of wavelengths distributed over a 10-20 nm wide band, these Fabry-Perot lasers self-mode-lock with no need for special mode-locking structures. Therefore they provide a simple multi-wavelength coherent comb source (CCS) with channel spacing determined by the laser cavity length. The unique properties of these lasers arise from the gain medium which is composed of millions of InAs semiconductor dots less than 50 nm in diameter. Each QD acts like an isolated light source interacting independently of its neighbours, and emits light at its own unique wavelength. In other words the InAs QD gain medium is inhomogeneously broadened, unlike the uniform semiconductor layers in quantum well (QW) lasers that are deployed in telecommunications today. The combination of this inhomogeneous broadening and mode-locking results in a coherent multi-wavelength laser source where each channel is inherently stable with lower intensity noise than comparable quantum well (QW) based semiconductor lasers [16-17].

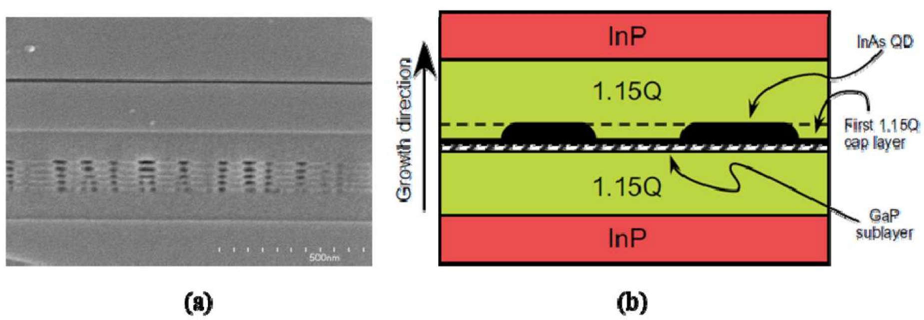



Fig. 1. (a) A cross sectional SEM image of the five-layer InAs/InP QDlaser core region and (b) a detailed structure for a single InAs/InP dot layer.

While the QD laser chips show great promise as practical comb sources, applications in future high speed networks must meet several demanding system requirements. Each channel must have extremely low noise, wavelength channels must be precisely locked to the system wavelength (or frequency) grid, and channel spacing must be precisely controlled. In this paper, we have successfully developed and fully characterized the first C-band QD CCL module with absolute wavelengths actively stabilized with respect to a reference etalon. The channel frequency spacing was set at 34.462 GHz maintained to within a ± 100 ppm accuracy.

## 2. InAs/InP QD laser and CCL module design

Figure 1 (a) and (b) show a cross sectional SEM image of the five-layer InAs/InP QD core region and its detailed structure for a single dot layer. The InAs/InP QD laser samples were grown by chemical beam epitaxy (CBE) on exactly (100) oriented n-type InP substrates [18]. The undoped active region of the QD sample consists of five stacked layers of InAs QDs with $In_{0.816}Ga_{0.184}As_{0.392}P_{0.608}$ (1.15Q) barriers. This active layer was embedded in a 355 nm thick 1.15Q alloy waveguide core that provides both carrier and optical confinement. This core is surrounded by p-doped (top) and n-doped (bottom) layers of InP and capped with a heavily doped thin InGaAs cap layer to facilitate the fabrication of low resistance Ohmic contacts. This QD laser diode was fabricated into single lateral mode ridge waveguide lasers with a ridge width of 2.0 μm. The devices were cleaved to form a Fabry-Perot (F-P) laser cavity approximately 1225 μm long, close to that required to achieve a free spectral range of 34.462 GHz. After mounting and wire-bonding the laser into a chip-on-carrier (CoC) platform, the c.w. lasing threshold current at 20°C was 39 mA with the slope efficiency of 0.14 mW/mA. The laser was driven with a DC injection current using our home-made ultra-low noise laser driver, and tested on a heat sink maintained at 20°C. The performance of the QD CCL was characterized using an optical spectrum analyzer (Anritsu MS9740A), an up to 50GHz PXA signal analyzer (Keysight Technologies Model N9030A), a wavelength and bandwidth tunable filter (Santec OTF-970), a 45 GHz IR photodetector (New Focus Model-1014), an optical autocorrelator (Femtochrome Research Inc FR-103HS), an Agilent N4371A relative intensity noise measurement system, an OE4000 automated laser linewidth / phase noise measurement system (OEWaves Inc.) and power meter (ILX Lightwave FPM-8210H).

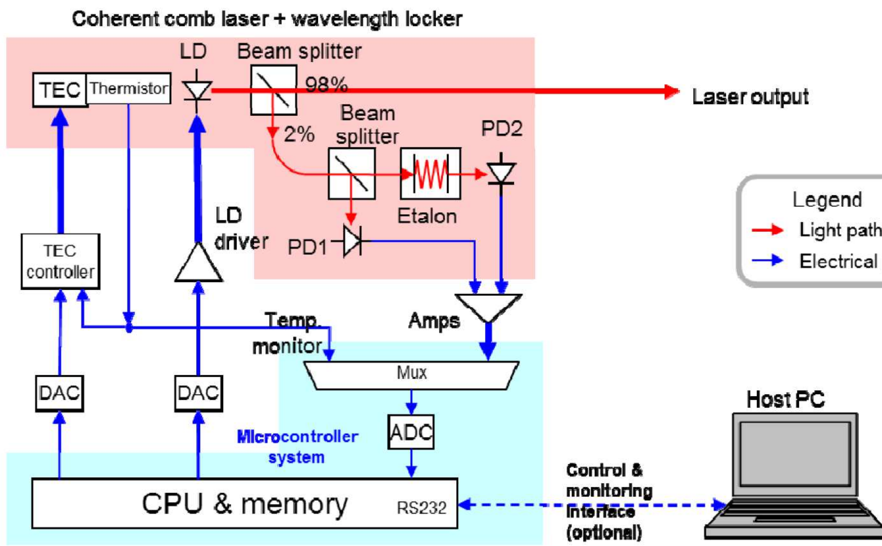
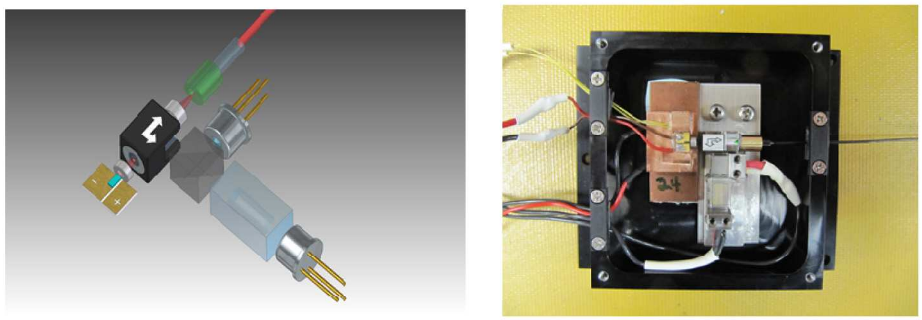



Fig. 2. Schematic of the QD CCL module design and its electrical control system.

The CCL module is shown schematically in Fig. 2. The laser was mounted on a thermoelectric cooler (TEC) for temperature control. Light output from this laser was sent through a collimating lens (not shown), a two-stage C-band optical isolator and beam splitter. After the beam splitter, one beam was focused into a single-mode optical fiber by another collimating lens. The second beam was sent through a second beam splitter that directed part of the light to a reference photodiode (PD1), and the rest of the light through a high-finesse etalon to another photodiode (PD2). The etalon transmission signal was used to monitor laser wavelength change. The etalon length and free spectral range (FSR) was designed to match the desired frequency grid spacing of 34.462 GHz. The rest of the system in Fig. 2 is a feedback loop that uses the signals from PD1 and PD2 as control input to stabilize the wavelength and output power by continuously adjusting laser current and temperature. The microcontroller is programmed to allow as a user to use a single command to adjust the either wavelength or power independently, – without affecting the other. Figure 3 (a) shows an optical design schematic of a QD CCL block, and Fig. 3 (b) shows the completed fiber pigtailed subassembly. All optical components were actively aligned and assembled. The QD CCL block has dimensions of 75 x 75 x 32 mm, and was integrated into 3U rack mountable case along with the power supply, microcontroller system and analog interface board. In our uncontrolled laboratory environment we have operated the QD C-band CCL module with the desired comb frequency spacing of 34.462 GHz, with comb frequency spacing and absolute wavelengths held to within ± 100 ppm and ± 0.01 nm, respectively, over a period of several weeks.

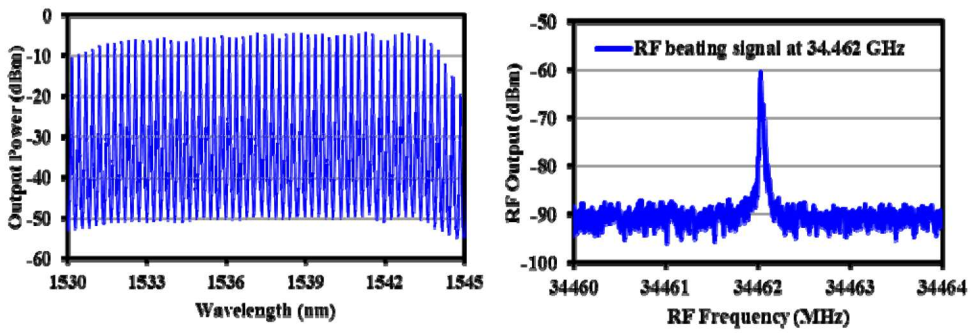


(a) (b)

Fig. 3. (a) An optical design schematic and (b) an actual optical fiber pigtailed subassembly of the QD CCL block.

## 3. Experimental results, noise performance analysis and discussions

Figure 4 (a) and (b) show the optical spectrum and RF beat spectrum of the InAs/InP QD C-band CCL module. The center wavelength is 1537.77 nm and the 3-dB comb bandwidth is 12 nm, providing 45 channels with an optical signal-to-noise ratio (OSNR) of more than 43 dB. The RF beat signal shown in Fig. 4(b) was obtained by focusing all wavelength channels simultaneously onto a fast photodiode and feeding the signal to an RF signal analyzer (Keysight N9030A 50 GHz PXA). The RF beat signal of 34.462 GHz is obtained for a QD laser drive current of 390 mA and an operating temperature of 20°C. The corresponding fiber coupled optical output power is 46 mW.




(a) (b)

Fig. 4. (a) Optical output spectrum of an InAs/InP QD C-band CCL module and (b) its RF beating frequency of 34.462 GHz between any two adjacent channels.

A programmable optical filter was used to select single wavelength channels and combinations of adjacent channels for measurement of inter-channel beat frequencies and channel noise. We clearly observed their RF beating frequency is 34.462 GHz with the RF linewidth of less than 10 kHz as shown in Fig. 4 (b). As a function of time, the laser output is a mode-locked pulse train with a measured periodicity of 29 ps, corresponding to the repetition rate of 34.462 GHz. The pulse train was characterized using optical intensity autocorrelation (Femtochrome Research Inc FR-103HS). The pulse width is approximately 800 fs at 390 mA and 20°C, with an extinction ratio of better than 20 dB. These results clearly indicate that the QD CCL module is an excellent mode-locked semiconductor laser source and the different channels are strongly phase-locked to each other [12,14-15].

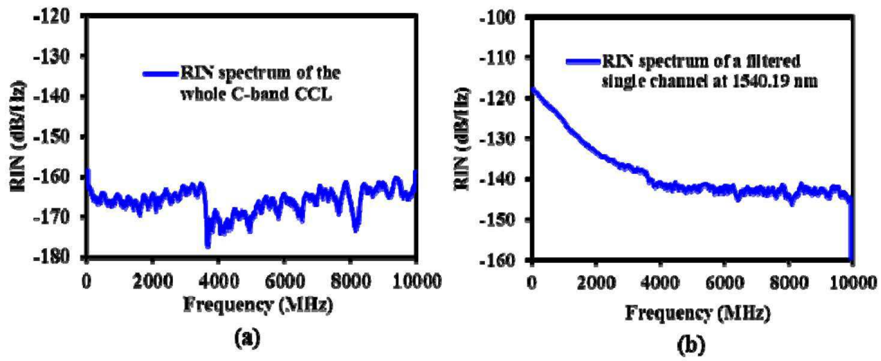



Fig. 5. (a) The RIN spectrum of the whole C-band CCL; (b) The RIN spectrum of one of the filtered 45 individual channels from the 34.462 GHz C-band QD CCL at an injection current of 390 mA and at 20°C.

Relative intensity noise (RIN) is a parameter representing temporal intensity fluctuations of a laser signal and is used to characterize the noise of the laser devices. In this work, we have used a commercial RIN measurement system (Agilent N4371A) to characterize intensity noise performance of both the combined CCL spectrum and individual channels isolated using a tunable filter (Santec OTF-970). The detailed RIN measurement and evaluation process is described in the N4371A RIN system product notes [19]. This instrument provides RIN values as ratio of the laser intensity noise to the average power, with the instrument thermal noise and photonic shot-noise contributions removed. The photonic shot-noise levels for the combined CCL spectrum at a power of 5 mW and the filtered single channel at 50 μW are estimated to be −162 dBm/Hz and −182 dBm/Hz, respectively. Figure 5 (a) and (b) give the RIN spectrum of both the full CCL spectrum at a total combined optical power of 5 mW and a filtered single channel at the wavelength of 1540.19 nm and with the optical power of 50 μW. All measurements were carried at 20°C. The integrated average RIN value of the combined comb is less than −165.6 dB/Hz on the frequency range from 10 MHz to 10 GHz, with the stated upper bound set by the instrument limited RIN measurement floor [19]. This is the lowest RIN value ever obtained from a semiconductor laser, to the best of our knowledge. The integrated average RIN value of the single channel at 1540.19 nm is −130.3 dB/Hz, again over the frequency range from 10 MHz to 10 GHz. The integrated RIN values for the other 44 filtered individual comb lines are also approximately −130 dB/Hz. These single-line RIN values are comparable to commercial quantum well DFB lasers and at least 15 dB lower than the RIN values from quantum well Fabry-Perot cavity lasers with an otherwise identical structure [20]. These low RIN results indicate that all wavelength channels of the CCL module are compatible with the requirements for data center Ethernet systems using data format PAM-4 at the data rate of 28 Gbaud [21].

The low single-line RIN from these Fabry-Perot lasers appears to be a unique property associated with the QD gain medium, since identical QW based structures have an average RIN 15 dB/Hz higher [20]. At this time the mechanisms that lead to stable multi-wavelength operation and mode-locking in quantum dot lasers are not fully understood and still topics of ongoing investigation. However a number of physical effects have been identified that may explain the exceptional properties of these lasers. The QDs are spatially isolated and carrier transport within the dot layer is poor [22] relative to that for QWs. It is this poor in-plane carrier diffusion, where the carrier diffusion time is longer than the typical carrier lifetime, which is believed to result in much stronger spatial hole burning (SHB) in QD lasers compared to their QW equivalent, a similar effect to that observed in quantum cascade lasers [23]. A recent theoretical study modelling the behavior of a QD multiwavelength laser [24] allowed the effect of SHB to be turned on or off. The SHB was found to be the fundamental physical effect at the origin of the multiwavelength lasing spectra. Under high drive current the theoretical model also predicted that the different lasing lines would phase lock resulting in a significant reduction in the calculated RIN. It is this phase locking of the modes which results in the pulse generation, i.e. mode-locking, observed in the QD lasers and the low single line RIN.

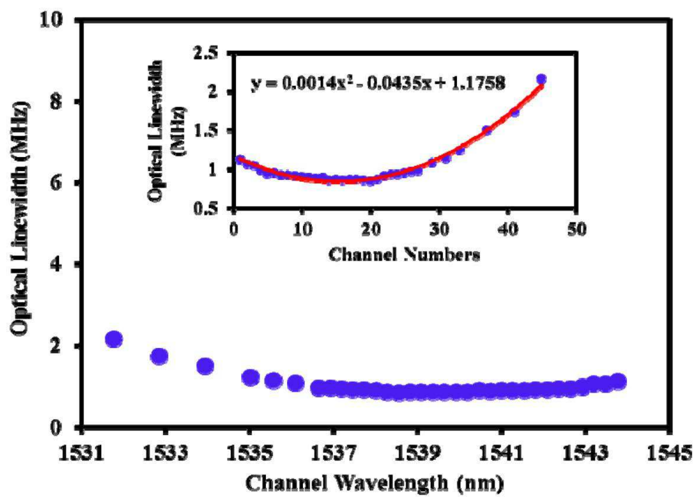



Fig. 6. Optical linewidth of each filtered channel versus channel wavelength from an InAs/InP QD C-band CLL at 390 mA and 20°C. The inset figure is its parabolic fitting curve and equation.

Phase or frequency noise is another critical parameter for lasers used in high speed and coherent communication systems. Figure 6 shows the measured optical linewidth of each channel of the 34.462 GHz C-band QD CCL versus channel wavelength from 1531.77 nm to 1543.77 nm at 390 mA and 20°C. The results indicate that the optical linewidth $\Delta\omega_N$ varies quadratically from 0.85 MHz to 2.16 MHz over the 45 channels [25]:

$$\Delta\omega_N = \Delta\omega_{\min} + \omega_{RF}(N - n_{\min})^2 \quad (1)$$

where $\Delta\omega_{\min}$ is the minimum value of a fitted parabolic curve for optical linewidth and $\omega_{RF}$ is the frequency separation between two adjacent channels. In this case, the fitted quadratic in Fig. 6 gives a minimum linewidth of approximately $\Delta\omega_{min}$ of 850 KHz and a phase noise increment is $\omega_{RF}$ of 1.4 KHz. The smallest linewidth occurs for $n_{\min}$ = 20 if we define the first channel (N = 1) wavelength as 1543.77 nm. The quadratic variation of the channel linewidth given by Eq. (1) can be derived by assuming that the phase noise variation from channel to channel is described by a Wiener process [25]. In this model, the phase noise variation from channel to channel is constrained by the mode-locking process, such that the phase variation between adjacent channels is much smaller than between widely separated channels. The channel wavelengths near $\Delta\omega_{\min}$ with the smallest phase noises are those channels with the highest output power. Those channels can initially produce enough nonlinear dispersion within the QD F-P cavity due to their stronger self-phase-modulation (SPM) and cross-phase-modulation (XPM) effects to compensate for the intrinsic linear dispersion [12]. The four-wave mixing (FWM) process between these dominant longitudinal modes creates a strong correlation between their phases. Subsequently, more distant longitudinal modes within the cavity are locked together. Eventually a highly coherent frequency comb with a repetition rate corresponding to the cavity round-trip time is generated [12, 14]. The optical linewidth of the initial channels that generate the FWM process has the smallest value [26]. Figure 6 also shows that 24 adjacent filtered channels have optical linewidths of less than 1 MHz, which is better than that of phase noises of most commercial QW DFB lasers.

## 4. Conclusion

In conclusion, we have successfully designed and demonstrated an actively stabilized 34.462 GHz C-band InAs/InP QD CCL module with the 45 individual channels. The comb frequency spacing and absolute wavelength have been held to within ± 100 ppm and ± 0.01 nm respectively, over a period of several weeks in an uncontrolled laboratory environment. The experimental results show that the integrated average RIN values of the whole C-band QD CCL and a filtered single channel at 1540.19 nm are −165.6 dB/Hz and −130.3 dB/Hz respectively, over the frequency range from 10 MHz to 10 GHz. The optical linewidth of individual channels arrayed between 1531.77 nm to 1543.77 nm, ranges from 850 KHz to 2.16 MHz including the 24 adjacent channels with optical linewidth of less than 1 MHz. These results have indicated that this QD CCL module is suitable as a coherent comb source for terabit optical networking systems by using PDM-QPSK [5] or 32-QAM [6] and PAM-4 [21] data formats at the base data rate of 28 Gbaud.