312-fs pulse generation from a passive C-band InAs/InP quantum dot mode-locked laser

Z.G. Lu*, J.R. Liu, S. Raymond, P.J. Poole, P.J. Barrios, and D. Poitras

Institute for Microstructural Sciences, National Research Council, Ottawa, ON, Canada
**Corresponding author: Zhenguo.Lu@NRC-CNRC.GC.CA*

Abstract: For the first time, we report femtosecond pulses from a passive single-section InAs/InP quantum-dot (QD) mode-locked laser (MLL) with the active length of 456 μm and ridge width of 2.5 μm at the C-band wavelength range. Without any external pulse compression, the transform-limited Gaussian-pulses are generated at the 92 GHz repetition rate with the 312 fs pulse duration, which is the shortest pulse from any directly electric-pumping semiconductor MLLs to our best knowledge. The lasing threshold injection current and external differential quantum efficiency are 17.2 mA and 38%, respectively. We have also investigated the working principles of the proposed QD MLLs.

OCIS codes: (230.5590) Quantum-well, -wire and –dot devices; (140.5960) Semiconductor lasers; (140.4050) Mode-locked lasers; (320.2250) Femtosecond phenomena; (190.4360) Nonlinear optics, devices.

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1. Introduction

The generation of femtosecond (fs) pulses with very high repetition rate has opened up new concepts in fs optical networking, signal processing and transmission [1]. In fact, semiconductor mode-locked lasers (MLLs) operating at the most important telecom C-band wavelength ranges from 1528 nm to 1565 nm and with tens-gigahertz or higher repetition rates are of great interest for many applications in high-capacity telecommunication systems, photonic switching devices, optical interconnects and all-optical clock recovery for very-large-scale integrated microprocessors and high-speed electro-optic sampling systems [2]. The MLL based on quantum-well (QW) semiconductor waveguide gain materials with Fabry-Perot cavity is an established technique for the generation of picosecond (ps) or sub-ps optical pulses with high-repetition-rate in the near-infrared spectral range [3]. The technological realization of high-quality and high-density self-assembled quantum-dot (QD) semiconductor materials offers one of the most promising systems for new semiconductor MLLs [4] because QD gain materials have much broad spectral gain bandwidths, better temperature stability, lower power consumption, and much faster carrier dynamics as compared with the same structure and doped QW- and quantum-dash-based semiconductor gain materials [5, 6]. Since the first passive QD MLL was observed by Huang et al [7] in two-section InAs/GaAs QD laser around 1.3 µm, passive mode-locking has also been reported using InAs/InP QD semiconductor materials with operating wavelengths around 1.5 µm [8, 9]. However, fs pulse generation with high repetition rate, already observed sub-ps pulses on Fabry-Perot (F-P) type lasers with QW and quantum dash active materials around 1.56 µm [3, 10], has not yet been reported in any passive single section QD-based semiconductor F-P type MLLs at the C-band wavelength range.

Recently, we have reported that a QD InAs/InP semiconductor F-P cavity chip was used to generate stable multi-wavelength laser systems at the L-band wavelength range from 1612 to 1632 nm because of highly inhomogeneous QD gain broadening due to statistically distributed sizes / geometries, composition and environment of self-assembled QDs [11]. In this paper, we present the first experimental demonstration of fs pulses from a single section monolithic InAs/InP QD F-P laser cavity. The device used for the demonstration had a cavity length of 456 µm and a ridge width of 2.5 µm with emission in the C-band wavelength range from 1528 nm to 1565 nm. The transform-limited Gaussian-pulses are generated at a repetition rate of 92 GHz with 312-fs pulse duration under continuous-wave (CW) injection operation mode and at a temperature of 18°C. To the best of our knowledge, the 312-fs pulse duration is the shortest pulse from any directly electric-pumping semiconductor MLLs without any external pulse compression scheme. The optical signal-to-noise ratio (OSNR) of the laser output spectra is up to 62 dB. The lasing threshold injection current is 17.2 mA and the external differential quantum efficiency of the QD laser is about 38%. The average output power is up to 13.2 mW when the injection current is 60 mA. We believe that the working principles of the proposed passive single section QD F-P type MLL are different from that of the saturable absorbers in other reported two-section QD MLLs [4, 7, 9]. Based on our experimental observation, we interpret that several nonlinear optical effects such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave-mixing (FWM) within the proposed QD MLL make the major contributions to lock the phases of the longitudinal modes of the QD F-P cavity, resulting in a train of 312-fs pulses with a repetition rate of 92 GHz corresponding to the cavity round-trip time.

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2. Experimental set-up, results and discussions

Figure 1 shows the experimental set-up of the QD MLL. The QD gain material structure consists of InAs QDs in an InGaAsP matrix on an InP substrate which could bring the advantages of QDs to the most important telecom C-band wavelength range from 1528 nm to 1565 nm. The QD gain material was based on a typical p-i-n configuration grown on an exactly (100)-oriented InP n-type substrate by chemical beam epitaxy (CBE). The undoped active region of the QD-laser consisted of five stacked layers of self-assembled InAs QDs embedded in 355 nm of $In_{0.816}Ga_{0.184}As_{0.405}P_{0.595}$ (1.15Q). From atomic force microscopy (AFM) measurements on similar uncapped stacked dot samples, the QD density in each QD layer was estimated to be approximately 3×10^{10} cm^{-2}. This core was vertically surrounded with an n-InP bottom cladding layer and a p-InP top cladding layer. The latter was covered with a cap of p^+-$In_{0.522}Ga_{0.478}As$ to ensure a good ohmic contact to the top metal stack. After processing into standard ridge waveguide structures, the sample was cleaved to a length of 456-µm and one facet was coated with a broadband high-reflectivity (HR) coating. This laser bar was mounted on a thermo-electric cooler (TEC) for temperature regulation, and a 2.5-µm wide ridge was selected and driven with CW injection current for testing. The laser output from the as-cleaved facet was coupled to a special fiber with high numerical aperture of 0.35, which was spliced with another single-mode fiber. The performance of the QD MLL was characterized using an optical spectrum analyzer (Ando AQ6317B), an optical autocorrelator (Femtochrome Research Inc FR-103HS), a digital phosphor oscilloscope (Tektronix TDS3054B), a delayed self-heterodyne interferometer (Advantest Q7332 and R3361A), and a power meter (Newport 840).

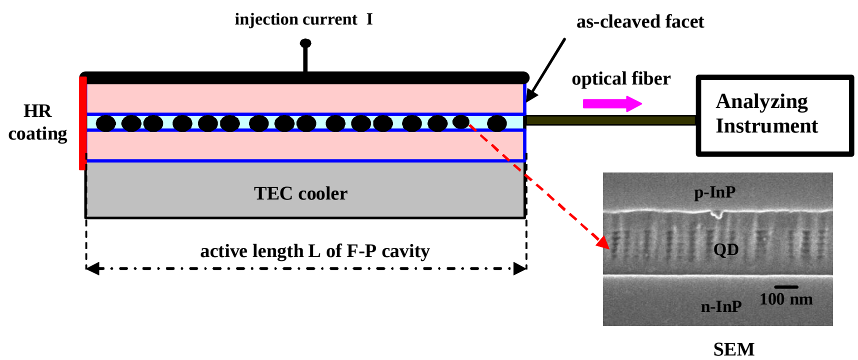

Fig. 1. Experimental set up of a passive single-section InAs/InP quantum dot mode-locked laser (MLL).

We have investigated the performance of the InAs/InP QD-based F-P laser at 18°C and under CW injection current operation. The lasing threshold injection current is 17.2 mA with the slope efficiency of 0.31 mW/mA. The lasing threshold current density per QD layer is less than 300 A/cm^2 and the external differential quantum efficiency around 1.55 µm is up to 38 %. The optical average output power is 13.26 mW for an injection current of 60 mA. Figure 2 shows the optical spectrum of the InAs/InP QD MLL at an injection current of 45 mA. The 3-dB spectral bandwidth around the centre lasing wavelength of 1541 nm is 11.62 nm as shown in Figure 2. The OSNR is up to 62 dB at the optical spectral resolution of 0.01 nm. The adjacent longitudinal mode spacing around the central wavelength of 1541 nm is 0.73 nm corresponding to a frequency spacing of 92 GHz. Self-mode-locking of this QD F-P laser occurred as soon as the injection current exceeded the lasing threshold current of 17.2 mA. The output pulse duration of the QD MLL is dependent on the injection current and the pulse duration reaches minimum when the injection current is 45 mA. Figure 3 gives the optical intensity autocorrelation pulse trains obtained by second-harmonic autocorrelation measurements when the injection current is 60 mA. The periodic time of the emitted pulse

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train measured is 10.87 ps, which corresponds to the repetition rate of 92 GHz and the free spectral range of 0.73 nm at the central wavelength of 1541 nm. The shortest pulse width was observed at an injection current of 45 mA where the autocorrelation signal of an isolated pulse was 442 fs, as shown in Figure 4. Some DC components or called the pedestal in both Figure 3 and Figure 4 was mostly coming from the optical autocorrelator because we have to use the maximum sensitivity of the photomultiplier tube detector with the 10-fs time resolution in order to obtain the strong enough second-harmonic generation (SHG) signals. If we subtract these DC components, the extinction ratio of pulses in time domain is approximately 15 dB. According to our fitting results between our experimental data of the QD-MLL pulses and Gaussian or Sech2 profiles, our current pulses are more similar to Gaussian shape. So converting to the real pulse duration by the factor of 0.707, we can obtain the shortest pulse width $\Delta\tau$ of 312 fs from this single section InAs/InP QD MLL, without any external pulse compression scheme. To the best of our knowledge, the 312 fs pulse duration is the shortest pulse from any directly electric-pumping semiconductor MLLs. Considering the 3-dB spectral bandwidth of 11.6 nm, the time-bandwidth product of $\Delta\tau\Delta\upsilon$ is 0.457, indicating that the pulse is very close to be a transform limited Gaussian-pulse. Because of the extremely broad gain bandwidth available when using QDs [5] and ultrashort relaxation time [6], we strongly believe that by further optimizing our InAs/InP QD waveguide structures and laser cavity design to minimize the intracavity dispersion effects and losses, sub-100 fs pulses from the proposed single section InAs/InP QD MML could be generated in the near future.

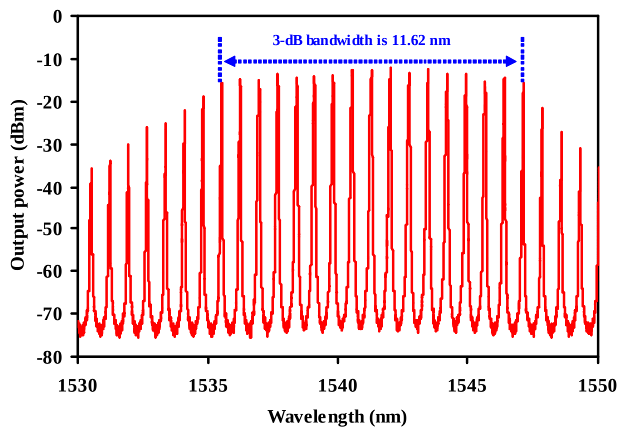

Fig.2. Optical spectrum of a passive single-section InAs/InP QD F-P mode-locked laser with an active length of 456 µm and ridge width of 2.5 µm at an injection current of 45 mA.

The working principles in passive single section QD F-P type MLLs are different from the saturable absorption effect in two-section QD MLLs. When the injection current is below the lasing threshold value, the intracavity waveguide gain material dispersion is linear and refractive index n_0 decreases with increasing wavelength λ [11]. This means that the adjacent longitudinal frequency spacings are not fixed due to the intracavity chromatic dispersion. When the injection current exceeds the lasing threshold current, the QD cavity lasing would be happening. Since the InAs/InP QD gain material is highly nonlinear [12] when lasing starts to occur the nonlinear dispersion effects within the QD cavity become significant. If the nonlinear index n_2 of the QD active material is positive, the center part of the beam transverse profile, where the intensity is higher, experiences a larger refractive index relative to the edges. The resulting nonlinear dielectric waveguide increases the beam confinement near its centre and hence narrows the beam diameter to an extent proportional to the optical power. This well-known self-focusing or Kerr-lensing effect refers to the waveguide lateral direction. As a

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result, a smaller beam diameter in turn leads to a decreased mode interaction with the QD waveguide metal-dielectric interface, which is a major source of waveguide losses within QD

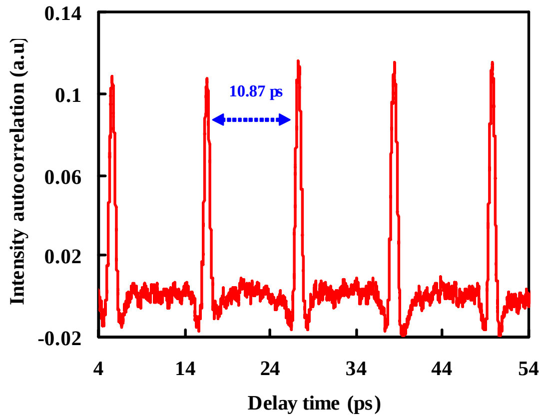

Fig. 3. Optical intensity autocorrelation pulse trains with the periodic time of 10.87 ps, which corresponds to a repetition rate of 92 GHz when the injection current is 60 mA.

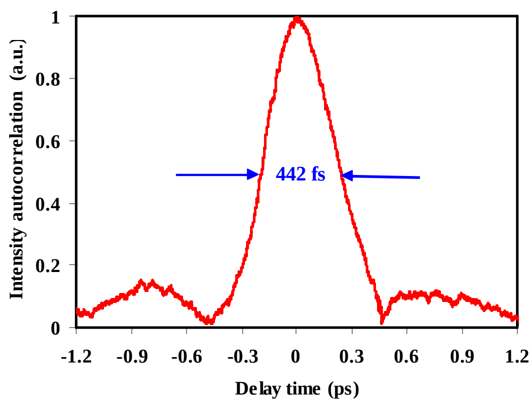

Fig. 4. Optical intensity autocorrelation trace with second-order autocorrelation measurements. Assuming a Gaussian pulse shape, the real pulse duration of the QD MML is estimated at 312 fs when the injection current is 45 mA at a temperature of 18°C.

semiconductor waveguide cavity. The net result is a decrease in the optical losses with increasing intensity, and it becomes favorable for the laser to obtain self pulsation process or to emit ultrashort pulses. In another words, these lasing modes lead initially to random intensity spike in the time domain, and subsequently to periodic pulse trains due to Kerr- lens effect based on self-focusing process if we believe that QD waveguides are also served as thick hard apertures, and any injection current fluctuation and temperature instability served as mode-locking starters. When this ultrashort pulse travels in a QD gain waveguide, it will further induce a variation of the refractive index of the QD waveguide due to the SPM or the optical Kerr effect. This variation in refractive index will produce a phase shift in the pulse, leading to a change of the pulse's frequency spectrum. At the same time, the optical intensity of one longitudinal mode will interact with another longitudinal mode within QD waveguide, so that the optical intensity of one longitudinal mode influences the phase change of another, so called XPM. Because of the strong SPM and XPM effects within the QD laser cavity the nonlinear dispersion is able to compensate the intrinsic linear dispersion and to minimize the intracavity dispersion effects, significantly enhancing the FWM process between the longitudinal laser modes within the QD F-P cavity. The enhanced FWM process can form a strong correlation between the phases of these longitudinal laser modes. In return, more and more longitudinal modes within the QD F-P cavity are locked together and are brought above lasing threshold. Eventually a train of ultrashort pulses with a repetition rate corresponding to the cavity round-trip time is generated.

In the proposed single section QD MLLs, the adjacent longitudinal frequency spacings at the different lasing wavelengths from 1532 nm to 1548 nm are identical, i.e. 92 GHz. That means that SPM and XPM effects in QD F-P cavity can create enough nonlinear dispersion to compensate the intracavity intrinsic linear dispersion, which will significantly enhance the FWM process of the longitudinal modes. Another evidence is the increase of the OSNR in Fig.2., up to 62 dB, which is mostly due to the very-strong nonlinear effects such as SPM, XPM, and FWM processes, and much less to the linewidth enhancement factor within QD waveguide gain materials. When the injection current is 45 mA, the average output power of the QD MLL is 8.6 mW and the pulse duration with the repetition rate of 92 GHz is 312 fs. This gives a peak power of 0.3 W and a peak power density within the InAs/InP QD cavity of up to 40 MW/cm^2. Such high peak power density can easily produce very-strong nonlinear effects such as SPM, XPM and FWM within InAs/InP QD gain materials. By using a delayed self-heterodyne interferometer and an RF spectrum analyzer, we have measured that the mode-beating linewidth of the proposed QD MML was less than 20 KHz, which is the resolution-limit given by the current 5-km delay optical fiber. Such a small mode-beating linewidth is clearly demonstrating that the phase fluctuations of these longitudinal modes of the QD F-P cavity are largely synchronized or correlated, as expected in a phase-mode-locked laser. It is worth to mention that the central lasing wavelength, average output power, pulse widths, 3-dB lasing bandwidth, and repletion rate of the proposed QD MLL are dependent on the injection current, the operation temperature, the QD waveguide structure and the different semiconductor material doped ratios, QD grown and waveguide process conditions, the coatings on the facets, and the physical length of the QD F-P cavity. For example, when we changed both the injection current and the operation temperature, the central lasing wavelength of 1541 nm was shifted within the range of a few nanometers and the corresponding pulse durations had also varied from 312 fs to 800 fs. But the changing of the repetition rate was within the tolerance range of the telecommunication ITU frame when the physical length of the QD gain material waveguide was fixed. More detailed relationships between these parameters of the proposed QD MLLs are still under investigation.

3. Conclusion

In this paper, we have experimentally demonstrated fs pulses from a single section monolithic semiconductor F-P laser cavity based on InAs/InP QD five-stacked layers grown by CBE. Transform-limited 312 fs Gaussian-pulses are generated at a repetition rate of 92 GHz without any external pulse compression scheme with an injection current of 45 mA at the temperature of 18°C. The OSNR of the laser output spectra is up to 62 dB. The lasing threshold current is 17.2 mA which corresponds to a lasing threshold current per QD layer of less than 300 A/cm^2. The external differential quantum efficiency is up to 38 %. Our investigation have also shown that several nonlinear optical effects such as SPM, XPM and FWM process within the QD gain cavity appear to be the major contributions leading to this strong passive phase mode-locking process. The mode beating linewidth of the proposed QD MLL was measured to be less than 20 KHz. Such an extremely narrow linewidth, compared to the bulk and QW countparts, leads to the excellent phase noise and time-jitter characteristics in actively mode-locking or directly high-speed modulation QD lasers. These promising results, largely attributed to the unique properties of QD gain materials, open a breakthrough direction to design high performance fs pulse sources and low timing-jitter components for ultra-high-bit-rate optical communications.