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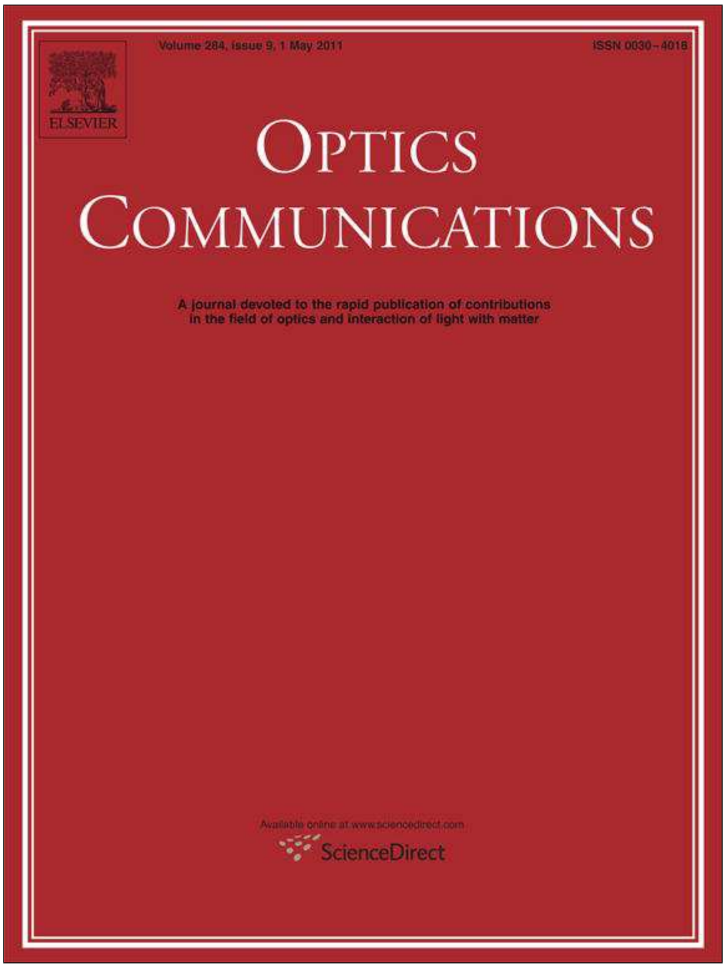
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Ultra-high repetition rate InAs/InP quantum dot mode-locked lasers

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A B S T R A C T

We have designed, grown and fabricated InAs/InP quantum dot (QD) waveguides as the gain materials of mode-locked lasers (MLLs). Passive InAs/InP QD MLLs based on single-section Fabry–Perot (F–P) cavities with repetition rates from 10 GHz to 100 GHz have been demonstrated in the C- and L-band. Femtosecond (fs) pulses with pulse duration of 295 fs have been achieved. The average output power is up to 50 mW at the room temperature of 18 °C. By using the external fiber mixed cavities fs pulse train with a repetition rate of 437 GHz has been generated. We have also discussed the working principles of the developed QD MLLs.

1. Introduction

Semiconductor mode-locked lasers (MLLs) have many photonic applications for optical communications due to their compactness, mechanical stability and robustness, high potential repetition rates and low potential jitters, which are very suitable for high-speed data transmission and switching, clock signal generation and electro-optic sampling [1]. As a result, monolithic MLLs have been extensively studied in bulk and quantum well (QW) semiconductor material systems for over 20 years [2]. However, typically these sources only generate pulses with durations of greater than 1 picosecond (ps). It has been predicted for many years that replacing bulk and quantum wells (QWs) with quantum dots (QDs) as the active gain medium for semiconductor lasers should result in a number of enhancements in laser device performance, such as reduced threshold current density [3], lower sensitivity of the threshold current to temperature (T_0) [4], reduced chirp [5], much broad spectral gain bandwidths [6] and much faster carrier dynamics [7]. Recently, QD MLLs have received much attention [8] due to their inherent properties, leading to hopes of improved performance. In 2001 Huang et al. [9] have demonstrated a QD MLL by using a two-section InAs/GaAs QD gain material with operation wavelength around 1278 nm. Now passive mode-locking has also been reported using InAs/InP QD semiconductor gain materials operating at wavelengths of around 1.5 μm [10–15].

In this paper, by using the InAs/InP QD layers as laser gain in a Fabry–Perot (F–P) cavity we have generated fs pulses with a pulse duration of 295 fs at the repetition rate of 50 GHz in the C-band operation wavelength range. To our best knowledge, the pulse duration of 295 fs is the shortest pulse from any directly electric-pumping semiconductor MLLs without any external pulse compression. Optical signal-to-noise ratio (OSNR) of the QD MLL is up to 60 dB. Average output power is up to 50 mW for the injection current of 300 mA at room temperature of 18 °C. Lasing threshold current and external differential quantum efficiency are 23 mA and 30%, respectively. We have indicated that several nonlinear optical effects related to the interaction of QD excitons with intracavity laser fields could create nonlinear dispersion to compensate intracavity linear dispersion. So total dispersion is minimized and four-wave mixing (FWM) is dramatically enhanced within QD F–P cavity. If spectral bandwidth is broad enough, tens or hundreds of longitudinal modes would lase and their phases would be locked together through FWM and other nonlinear effects. Eventually a train of fs pulses with a repetition rate corresponding to cavity round-trip time is generated. By changing the active length of F–P cavity, we have demonstrated QD MLLs with different repetition rates from 10 GHz to 100 GHz. We have also successfully demonstrated optical pulse train generation with the repetition rate of 437 GHz by using fiber-based grating coupled external cavities and InAs/InP QDs as the gain materials. 437 GHz is the highest repetition rate pulse train ever produced by InAs/InP QD lasers.

2. QD materials, set-up, results and discussions

Fig. 1 has showed the schematics of the proposed InAs/InP QD MLL. The InAs/InP QD laser samples used in this study were grown by

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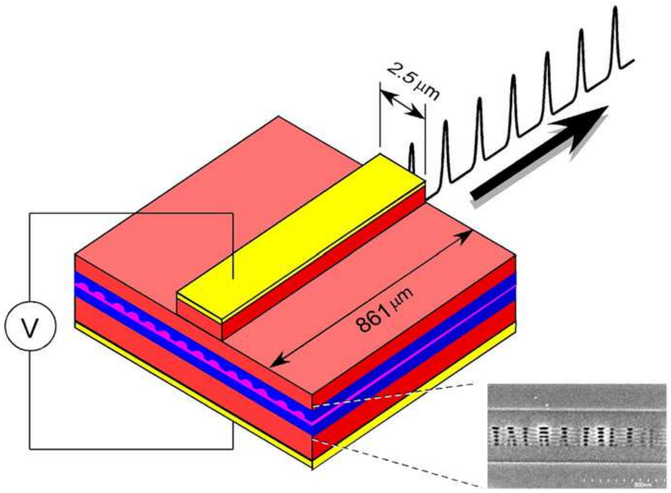

Fig. 1. Schematics of the proposed monolithic InAs/InP QD MLL.

chemical beam epitaxy (CBE) on exactly (100) oriented n-type InP substrates. The undoped active region of the QD sample consisted of five stacked layers of InAs QDs with $In_{0.816}Ga_{0.184}As_{0.392}P_{0.608}$ (1.15Q) barriers. The QDs were tuned to operate in the C- or L-band using a QD double cap growth procedure and a GaP sublayer [16,17]. In the double cap process the dots are partially capped with a thin layer of barrier material, followed by a 30 s growth interruption and then complete capping. The thickness of the partial cap controls the height of the dots, and hence their emission wavelength. It also helps to narrow the height distribution of the dots, and therefore narrow the 3-dB gain spectrum. Growing the dots on a thin GaP layer allows a high dot density to be obtained and improved layer uniformity when stacking multiple layers of dots, providing maximum gain. This active layer was embedded in a 355 nm thick 1.15Q waveguiding core, providing both carrier and optical confinement. An average dot density of approximately 3.5×10^{10} cm^{-2} per layer was obtained. The waveguiding core was surrounded by p-doped (top) and n-doped (bottom) layers of InP and capped with a heavily doped thin InGaAs layer to facilitate the fabrication of low resistance Ohmic contacts. The sample was fabricated into single lateral mode ridge waveguide lasers with a ridge width of 2.5 µm, and then cleaved to form an F–P laser cavity. One facet had a broadband high reflectivity (HR) coating and the other was left as-cleaved and was used as the output facet. This was coupled to an anti-reflection (AR) coated lensed fiber followed by a C- or L-band optical isolator to reduce any back-reflection to the laser. The laser was driven with a DC injection current, and tested on a heat sink maintained at 18 °C. 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. 2(a) and (b) shows typical optical spectra of C- and L-band from the proposed F–P QD MLL with the active length of 861 µm for an injection current of 180 mA and at the temperature of 18 °C. The center wavelengths are around 1539 nm for C-band and 1586 nm for L-band. Their both 3-dB bandwidth is bigger than 12 nm, suggesting the capacity to obtain fs pulses and covering over 30 channels with 50 GHz frequency spacing. The OSNR of the laser output spectra is up to 60 dB. The experimental results indicated that the lasing threshold current is 23 mA with the slope efficiency of 0.227 mW/mA. The lasing threshold current density per QD layer is less than 214 A/cm^2 and the external differential quantum efficiency around 1540 nm is up to 30%. The optical average output power measured by a large area detector is 50 mW when the injection current is 300 mA at the operation temperature of 18 °C. When we change the active lengths of F–P

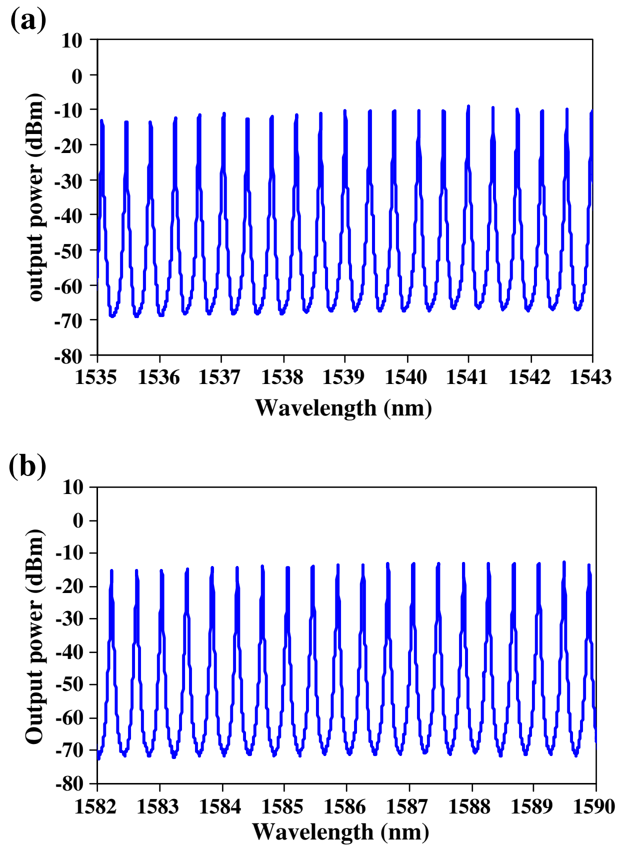

Fig. 2. Typical optical spectrum from the developed InAs/InP QD MLLs for an injection current of 180 mA at the room temperature of 18 °C. The active length is 861 µm which corresponds to the 50 GHz repetition rate. (a) C-band; (b) L-band.

cavity to 430 µm and 4300 µm, we have obtained the InAs/InP QD MLLs with the repetition rate of 100 GHz and 10 GHz, respectively. Fig. 3(a) and (b) has shown their corresponding optical spectra.

Measurements are made in the temporal domain with a self-referenced intensity autocorrelator based on second harmonic generation. Fig. 4 shows a long scan pulse train autocorrelation signal which exhibits the 20 ps periodic time of the emitted pulse train, corresponding to the repetition rate of 50 GHz and the free spectral range (FSR) of 0.40 nm at the central wavelength of 1540 nm. The autocorrelation signal of an isolated pulse is shown in Fig. 5. The autocorrelation pulse width is measured to be 417 fs. According to our fitting results between our experimental data of the QD-MLL pulses and Gaussian or Sech^2 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 a real pulse width $\Delta\tau$ of 295 fs at the output of the laser, without any external pulse compression scheme. To the best of our knowledge, the 295 fs pulse duration is the shortest pulse from any directly electric-pumping semiconductor MLLs. Considering the 3-dB spectral bandwidth of 17.9 nm, the time-bandwidth product of $\Delta\tau\Delta\upsilon$ is 0.66, indicating that there is some residual frequency chirp being present in the pulses.

Now we would like to discuss this self-mode-locking working principle. The proposed MLL mechanism need to be explained together with the QD gain materials' unique properties. Due to the statistically distributed sizes, geometries, compositions, and confinements, electrically pumped self-assembled QDs have highly imhomogeneously-broadened ASE spectra with the 3-dB bandwidth up to hundreds of nanometers [6]. Once those ASE spectra are laterally confined by waveguides, longitudinally selected and enhanced by a F–P cavity, lasing could occur over a broadwide wavelength range where intracavity gain is larger than waveguide internal loss plus cavity

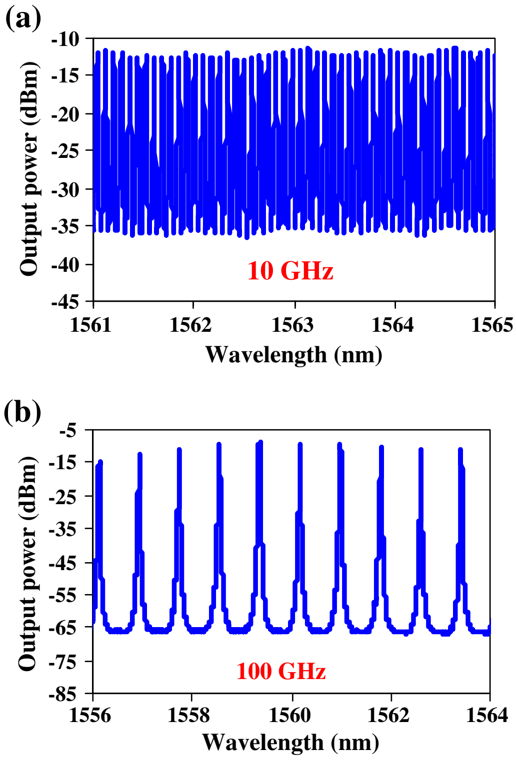

Fig. 3. (a) and (b) Typical optical spectrum from the developed InAs/InP QD MLLs with the repletion rate of 10 GHz and 100 GHz, respectively.

mirror losses. Because this type of inhomogeneous gain dramatically suppresses mode competition, very stable QD multi-wavelength laser (QD-MWL) has been obtained in such QD F–P cavity with tens or hundreds of longitudinal lasing modes [18,19]. Because of the intracavity intrinsic linear dispersion from QD waveguide and facet mirror coatings, the QD-MWL has the minor non-equal mode spacing between any adjacent longitudinal modes. When the injection current exceeds the certain values, the minor non-equal mode spacing could simultaneously be corrected by intracavity nonlinear dispersion effect related to the interaction of QD excitons with intracavity laser fields. So the adjacent longitudinal frequency spacing of the QD-MWL becomes equal over a broadwide lasing wavelength range. In this case, total dispersion is minimized and FWM is dramatically enhanced within the QD F–P cavity [20,21]. If this spectral bandwidth is broad enough, tens or hundreds of longitudinal modes would lase and their phases would be locked together through FWM and other nonlinear processes, such as self-phase modulation (SPM) and cross-phase modulation (XPM). These phase-locked lasing modes lead initially to random intensity spike in the time domain, and subsequently to

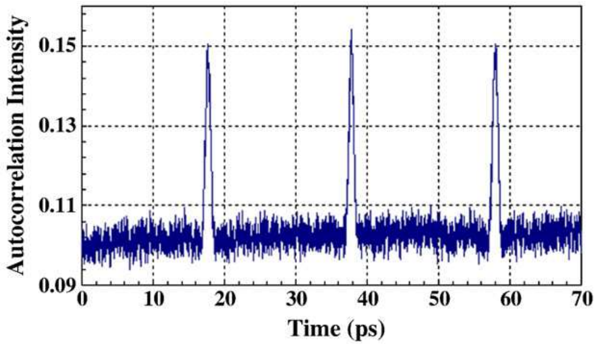

Fig. 4. Optical intensity autocorrelation pulse trains with the periodic time of 20 ps, which corresponds to the repetition rate of 50 GHz.

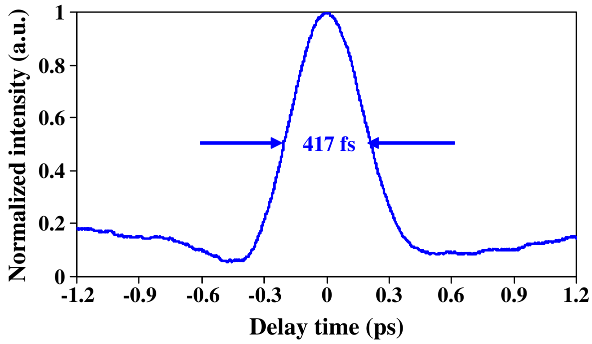

Fig. 5. Optical intensity autocorrelation trace with the second-order autocorrelation measurements. Assuming a Gaussian-shaped pulse, the real pulse duration of the QD MML is estimated at 295 fs when the injection current is 200 mA at a temperature of 18 °C.

periodic pulse train due to Kerr-lens effect based on self-focusing, and any small injection current variation and temperature instability serve as mode-locking starters. Eventually a train of ultrashort pulses with a repetition rate corresponding to the cavity round-trip time is generated. 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.

For single-section F–P cavity-based QD MLLs, the repetition rate is reversely proportional to the cavity length, which limits to realize higher repetition rates. In order to increase the pulse repetition frequency, other research groups have utilized the group-velocity dispersion of optical fiber [22] or extracted every N_{th} lasing mode at the outside of the laser cavity using appropriate optical fiber [23] to multiply repetition frequency of mode-locked pulses. In this paper, we have made use of eight fiber Bragg gratings (FBGs) with equal frequency spacing and InAs/InP QDs as the gain material to build up the external fiber mixed cavities as shown in Fig. 6. Optical light was coupled out and back into the QD F–P cavity by an AR coated lensed fiber. Reflected light by eight FBGs was transmitted back into the QD F–B cavity by a 3-dB coupler. Fig. 7 shows the measured optical spectrum from the external fiber mixed cavities including the QD F–P cavity plus eight external cavities formed by eight FBGs with equal frequency separation. The whole spectrum is located in C band with the centre wavelength of 1540 nm. Longitudinal modes, marked by B in Fig. 7, are generated by the stimulated emission in the QD F–P cavity due to the uncoated facets with reflectivity of approximately 33%. It is seen that the whole spectrum is very broad and consists of many spectral components. When the optical light is transmitted from the QD F–P cavity to the FBGs, only longitudinal modes matching with the wavelengths of the FBGs are reflected back by the external cavities

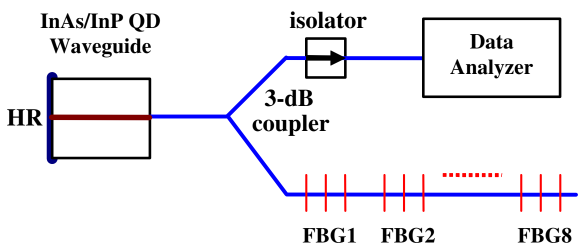

Fig. 6. Schematic of the external fiber mixed cavities including the InAs/InP QD F–P cavity plus eight external cavities formed by eight FBGs with equal frequency separation.

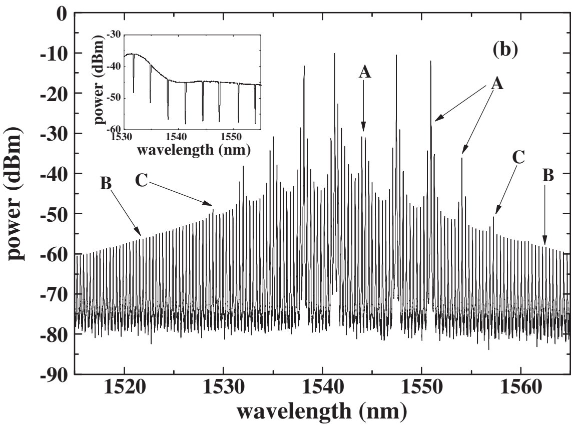

Fig. 7. Optical spectrum from the external fiber mixed cavities. Longitudinal modes marked by A, B and C are generated by external cavities, QD F–P cavity, and FWM, respectively. Inset: Reflection wavelength spectrum of the eight FBGs.

and their intensity is increased. Other longitudinal modes are transmitted through. As a result, eight high peaks with optical power from −40 dBm to −10 dBm and equal spacing in the C band are clearly observed in the spectrum, marked as A in Fig. 7. They were stimulated by the FBGs in external cavities. The QD F–P cavity provides necessary conditions for pulse generation. These selected modes were amplified and phase locked in the QD F–P cavity to achieve mode-locking laser. By using the intensity autocorrelator, a pulse train with a period of 2.29 ps was exhibited on the oscilloscope, corresponding to a 437 GHz repetition rate as shown in Fig. 8. The period is determined by the free spectral range (FSR) of the QD F–P cavity as well as the frequency spacing of the FBGs. The formation of the pulse train demonstrates the successful mode-locking in the QD-based external cavities. By assuming Gaussian shape and using the conversion factor of 0.707, the real pulse width is approximately 810 fs. The average output power of the pulses is about 1 mW and the peak power is about 2.825 mW. The peak power density is 235 KW/cm^2. As our best knowledge, 437 GHz is the highest repetition rate pulse train ever produced by InAs/InP QD lasers.

3. Conclusions

We have demonstrated passive single-section monolithic InAs/InP QD MLLs which can operate in both C- and L-band wavelength range. 295-fs pulses with a repetition rate of 50 GHz were generated without any external pulse compression scheme at the room temperature of 18 °C. The lasing threshold injection current was less than 23 mA and the lasing threshold current per QD layer for single mode ridge waveguide QD lasers was less than 214 A/cm^2. The external differential quantum efficiency around 1540 nm was up to 30%. By changing the F–P cavity lengths and using the external fiber mixed cavities, we had also demonstrated InAs/InP QD MLLs with repetition rates of 10 GHz, 100 GHz and up to 437 GHz, respectively. Their working principles of the developed QD MLLs have been discussed. 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 and signal process.

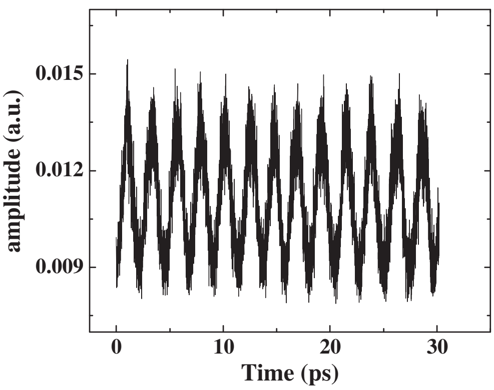

Fig. 8. Autocorrelation of the pulse train with the periodic time of 2.29 ps, which corresponds to the repetition rate of 437 GHz.

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