Optics Communications 284 (2011) 2323–2326

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

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

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ARTICLE INFO

Article history:
Received 29 September 2010
Received in revised form 27 November 2010
Accepted 29 November 2010
Available online 13 December 2010

Keywords:
Quantum dot
InAs/InP semiconductor materials
Mode-locked laser
Fabry–Perot cavity
C- and L-band
Femtosecond pulses
High repetition rate

ABSTRACT

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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doi:10.1016/j.optcom.2010.11.083

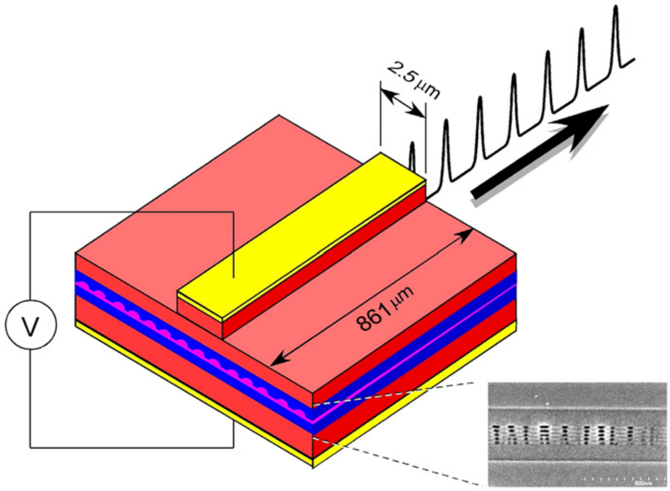

Fig. 1. Schematics of the proposed monolithic InAs/InP QD MLL.

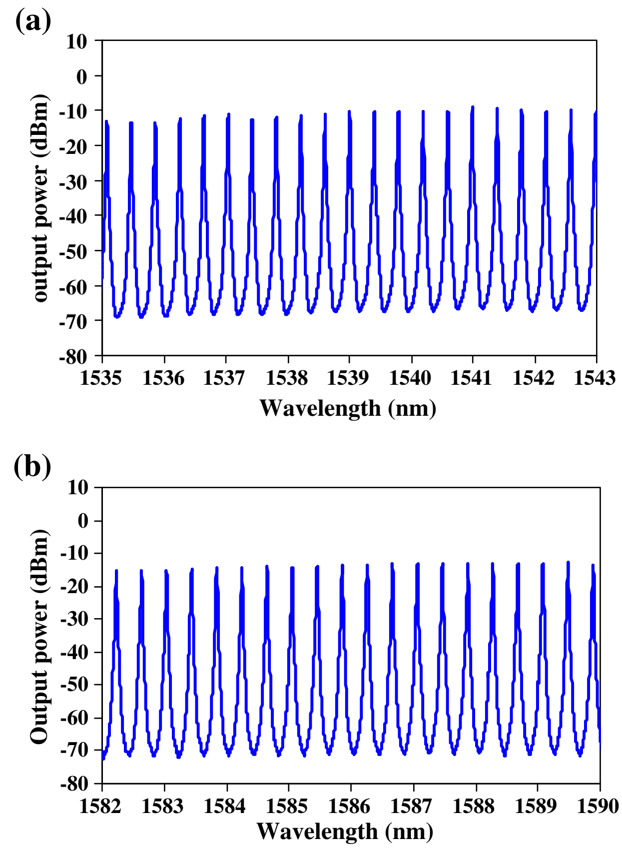

Fig. 2. Typical optical spectrum from the developed InAs/InP QD MLLs for an injection current of 180 mA at the room temperature of 18 °C. The active length is 861 μm which corresponds to the 50 GHz repetition rate. (a) C-band; (b) L-band.

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 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