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Single-section mode-locked 1.55-μm InAs/InP quantum dot lasers grown by MOVPE

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ABSTRACT

We report on ultra-short pulse single-section mode-locked lasers emitting at 1.55 μm, based on self-assembled InAs/InGaAsP/InP quantum dot active regions grown by metal-organic vapor phase epitaxy (MOVPE). For a 1.5-mm-long Fabry-Perot laser, mode-locking at a repetition rate of 29.8 GHz with pulse duration of 855 fs is obtained without any external pulse compression techniques. The mode-beating exhibits a narrow RF linewidth less than 30 kHz, and a wide frequency tuning range up to 73 MHz can be achieved by simply changing the injection current. Moreover, a higher repetition rate of 55.6 GHz and the transform limited Gaussian-pulse with the 707 fs pulse duration are achieved from a device with a shorter cavity length of 0.8 mm.

1. Introduction

The development of semiconductor mode-locked laser (MLL) diodes for high repetition frequency and low-noise short pulses is of key importance for a wide range of applications, including frequency comb generation [1], biomedicine [2] and optoelectronic oscillator for millimeter-wave generation [3]. In particular, short pulse sources emitting in the 1.55-μm wavelength window are well suited for high-speed optical time-domain multiplexed systems [4], and all-optical signal-processing including optical clock recovery applications [5]. Traditionally, bulk or quantum-well (QW) active materials were used to achieve the MLL emitting in the 1.55-μm wavelength band [6]. Recently, MLL based on the self-assembled quantum dot (QD) gain material have attracted more attention due to their inherent broadband spectrum [7], low linewidth enhancement factor [8], ultrafast carrier dynamic [9], and low amplified spontaneous emission [10]. Most of the advantages have been well demonstrated for the MLL based on self-assembled InAs/GaAs QD material [11], but it is difficult to reach the C and L bands based on this material system. More recently, self-assembled InAs/InP QD or quantum dash (QDash) materials have been an area of strong research interests. Subpicosecond pulse generation [12], and repetition rates as high as 346 GHz [13] have been achieved for the single-section QDash MLL grown by gas source molecular beam epitaxy (GSMBE). Meanwhile, QDs grown by GSMBE on misoriented (100) [14] or (113) B InP substrates [15] and chemical beam epitaxy (CBE) have also demonstrated good mode-locking performances in single-section devices [16]. In comparison, only a few reports have been reported on InAs/InP QD-ML lasers grown using metal organic vapor phase epitaxy (MOVPE), where progresses have been hindered by complicated growth kinetics and the situ monitoring techniques are still in its infancy [17]. However, MOVPE growth technique remains an important epitaxial approach considering its broad capability for growing a variety of semiconductor compounds, as well as its scalability to batch production and the well demonstrated commercial laser reliability performance. Up to now, the reported MOVPE grown QD-MLL are based on the conventional monolithic two-section structure. The first results obtained by Heck et al. from this approach showed very elongated pulses with a chirp value of 20 ps/nm [18]. More recently, a frequency tuning range of 300 MHz has been reported by adjusting the reverse bias voltage of the saturable absorber and the gain section current, with a minimum pulse width of 3.7 ps [19].

In this paper, we experimentally investigate the single-section InAs/InGaAsP/InP QD MLL emitting at the 1.55-μm wavelength band grown by MOVPE for the first time. Mode-locking at a repetition rate of 29.8 GHz with pulse duration of 855 fs is demonstrated for a 1.5-mm-long Fabry-Perot laser without any external pulse compression techniques. A RF spectral width less than 30 kHz is achieved, demonstrating its low timing jitter properties. By simply adjusting the injection current, a wide frequency tuning range up to 73 MHz can be obtained. Moreover, for a 0.8-mm-long

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device, transform limited Gaussian-pulse at a repetition rate of 55.6 GHz is observed with the pulse duration down to 707 fs.

2. Device fabrication and experimental setup

The QD gain material is grown on exactly (100)-oriented InP n-type substrates by MOVPE. The active region of the QD-lasers consist of seven stacked layers of InAs QDs embedded in a 140-nm-thick InGaAsP waveguide with a room-temperature bandgap wavelength of 1.1 µm (1.1 Q). Fig. 1(a) shows a photoluminescence (PL) spectrum of the QD active region at room temperature. The PL peak wavelength is located at 1580 nm, and the full width at half maximum (FWHM) of 183 nm is obtained. The broad spectrum is mainly attributed to the inhomogeneous size dispersion of InAs QDs within the seven stacked QD layer. The waveguide core is vertically surrounded with n-doped (bottom) and p-doped (top) layers of InP. The latter is covered with 150-nm-thin heavily doped InGaAs layer to ensure low-resistance ohmic contacts. More details of material growth can be found elsewhere [20]. Single-section FP ridge waveguide lasers with a stripe width of 6 µm are fabricated using standard optical lithography and wet etching process, then the samples are cleaved to lengths of 1.5 mm and 0.8 mm, respectively. Fig. 1(b) shows schematic diagram of the apparatus used for the measurement of the QD MLL. The QD MLL is mounted on a thermo-electric cooler (TEC) to control its operating temperature at 18 °C. The laser signal is coupled to an anti-reflection coated lensed fiber and then amplified by an Erbium-doped fiber amplifier (EDFA). An optical spectral analyzer (OSA, Advantest Q8384), an electrical spectral analyzer (ESA, Agilent PXA N9030A) with a 50-GHz photodetector (U^2T XPDV2320R) and an optical autocorrelator (A.P.E. pulsecheck autocorrelator) are also used to characterize the performances of the QD MLL.

3. Mode-locking characterization and discussions

The mode-locking performance of a single-section InAs/InP QD laser with a cavity length of 1.5-mm and a ridge width of 6 µm is investigated firstly under the continuous-wave (CW) injection

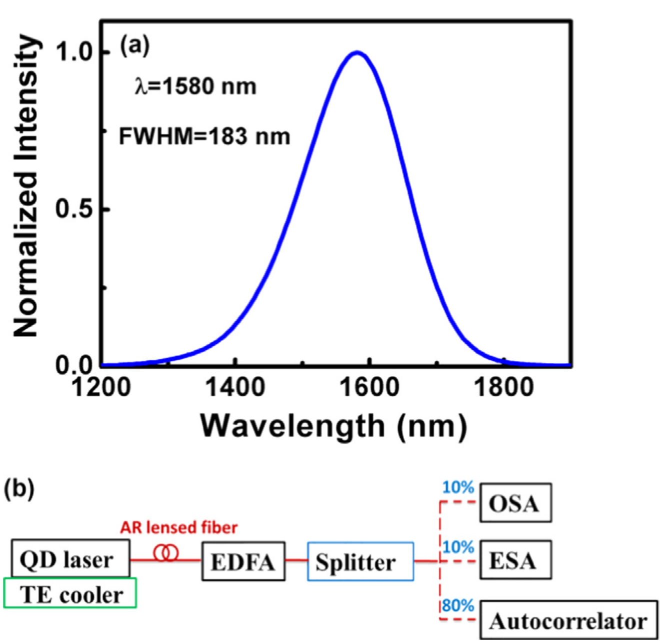

Fig. 1. (a) RT PL spectrum of the QD active region. (b)Schematic diagram of the test setup used for the QD MLL.

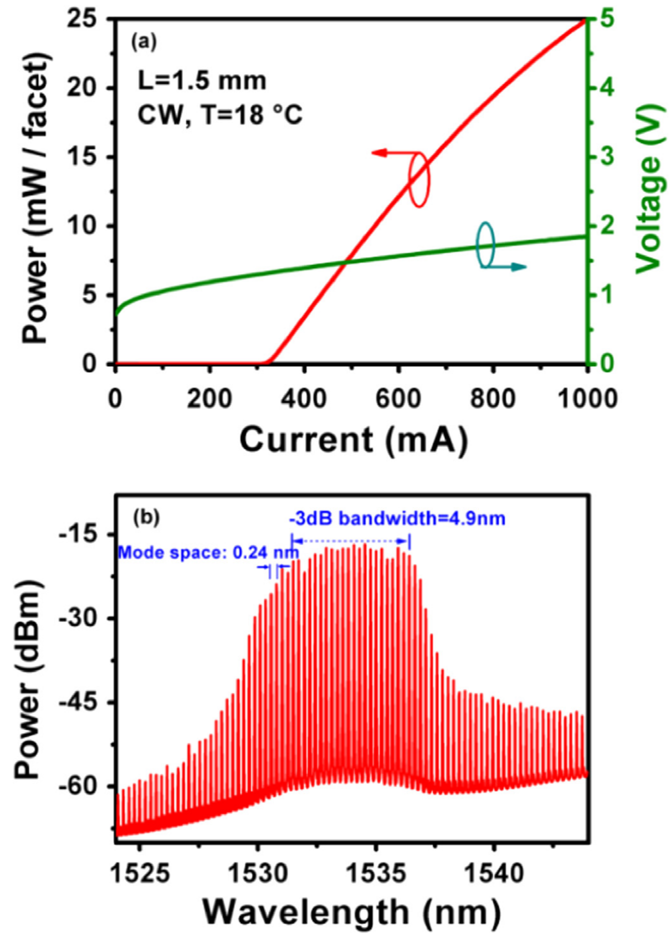

Fig. 2. (a) CW light-current and voltage-current characteristic curves, and (b) lasing spectrum at the injection current of 600 mA for a single-section QD-MLL with a cavity length of 1.5 mm and a ridge width of 6 µm.

current at 18 °C. Fig. 2(a) shows the light output power (*L–I*) and applied voltage versus the CW injection current (*V–I*) curves for the MLL. The lasing threshold current is 320 mA, corresponding to a threshold current density of 507 A/cm^2 per QD layer. An average output power per facet of 28 mW under an injection current of 1000 mA is achieved. Fig. 2(b) shows the lasing spectrum of the MLL at an injection current of 600 mA, and a −3dB spectral bandwidth of about 4.9 nm is obtained around the central lasing wavelength of 1533 nm. The broad optical spectral bandwidth obtained here can be attributed to the inhomogeneous broadening of the QD assembly due to its large fluctuations of effective volume and composition.

The RF spectra are measured using an ESA connecting to a 50 GHz bandwidth InGaAs photodiode detector for the 1.5-mm-long single-section QD laser. Fig. 3(a) shows the variation of the repetition frequency and 3 dB RF linewidth of the MLL as a function of injection current. From the figure, it can be clearly seen that the repetition frequency approximately decreases linearly with the increasing injection current, which can be attributed to two possible factors. One is the increase of thermal escape of carriers with increasing injection current, which results in an increase of refractive index n_r [21]. The other factor is the increasing physical cavity length due to the thermal expansion of waveguide under the large CW injection current. The increments of the n_r and cavity length can both lead to a reduction of the ML repetition frequency. A large RF linewidth at the low injection current is also observed in Fig. 3(a), which can be explained by the fact that the intracavity nonlinearities and phase correlation among the longitudinal laser