Above threshold spectral dependence of linewidth enhancement factor, optical duration and linear chirp of quantum dot lasers

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Abstract: The spectral dependence of the linewidth enhancement factor above threshold is experimentally observed from a quantum dot Fabry-Pérot semiconductor laser. The linewidth enhancement factor is found to be reduced when the quantum dot laser operates ~ 10 nm offset to either side of the gain peak. It becomes significantly reduced on the anti-Stokes side as compared to the Stokes side. It is also found that the temporal duration of the optical pulses generated from quantum dot mode-locked lasers is shorter when the laser operates away from the gain peak. In addition, less linear chirp is impressed on the pulse train generated from the anti-Stokes side whereas the pulses generated from the gain peak and Stokes side possess a large linear chirp. These experimental results imply that enhanced performance characteristics of quantum dot lasers can be achieved by operating on the anti-Stokes side, ~ 10 nm away from the gain peak.

OCIS codes: (140.5960) Semiconductor laser; (140.4050) Mode-locked laser; (140.3520) Laser, injection-locked; (250.5590) Quantum-well, -wire and -dot devices.

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1. Introduction

Semiconductor lasers based on quantum dots (QD) have been intensively investigated because of the expected properties of quantum dots which are low threshold current with less temperature sensitivity, near zero linewidth enhancement factor (LEF), and large differential gain and modulation bandwidth [1–4]. The LEF affects linewidth, chirp, and filamentation as well as the overall semiconductor laser dynamics such as noise and optical injection [5].

The LEF of QD semiconductor lasers above threshold is expected to be small because of the expected high differential gain and symmetric gain spectrum which arises from the delta function like density of states of QD, however the reported LEF of QD lasers above threshold is similar to that of quantum well lasers, or can be substantially larger ~ 57 [6-7]. It has been theoretically and experimentally studied that the LEF of a QD laser can be changed considerably by the photon energy, carrier density, inhomogeneous broadening, contribution of excited states, and carrier temperature [8–11].

In this paper, we investigate LEF in both continuous wave and mode-locked QD lasers. We also investigate the pulse duration and chirp with respect to the different spectral regimes when the QD lasers are oscillating above threshold.

2. Experiment

For this experiment, Fabry-Pérot (F-P) and curved two-section devices incorporated with an external cavity for mode-locking are fabricated from a commercial QD wafer (Innolume GmbH) which has ten layers of self-assembled InAs/GaAs quantum dots, covered with 5 nm $In_{0.15}Ga_{0.85}As$. The QD lasers have a ridge waveguide width of 4 μm and have uncoated facets. The QD lasers are temperature controlled to operate at room temperature, using a thermoelectric controller.

2.1 Spectral dependence of LEF above threshold

LEFs above threshold are measured by an injection locking method [12–14]. A QD based tunable laser coupled with a grating (1200 line/mm) in Littman/Metcalf configuration is constructed as a master laser and a QD F-P laser with 734 μm length is used as a slave laser. The length of the QD F-P is carefully chosen to have a large free spectral range for ground state lasing because simultaneous lasing or only excited state lasing is dependent on the cavity length due to the small density of states on the ground state and the finite interband relaxation time [15-16]. A free spectral range of 58 GHz for the QD F-P laser is measured with an injection current of 45 mA (2 × threshold). The optical injection power to the slave laser is controlled by a neutral density filter and fine optical frequency tuning between the master and slave laser is achieved by introducing a very small change in temperature of the gain medium

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of the slave laser through a thermoelectric controller. The resistance change of 100 Ω of the temperature controller corresponds to a temperature change of 0.149 °C and causes a 3 GHz shift of F-P modes. A high resolution (~ 2 GHz) optical spectrum analyzer (OSA) is used to measure the frequency offset between the tunable laser and the target longitudinal mode of the slave laser. Locking is defined here when suppression of side modes is over 40 dB with a given injection power. The LEF measurement is performed on five different wavelengths of ground state, i.e., one around the gain peak (λ_1 = 1264 nm) where lasing occurs, and two each for the anti-Stokes (λ_2 = 1254 nm and λ_3 = 1259 nm) and Stokes side (λ_4 = 1269 nm and λ_5 = 1274 nm) with respect to the gain peak as shown in Fig. 1 (a). Figure 1 (b) shows optical spectra of free running and injection locked QD F-P laser and wide span of injection locked optical spectrum is shown in Fig. 1 (c). The measured locking bandwidth for each of the five different spectral regimes is shown in Fig. 1 (d) ~ (h). The observed asymmetric locking bandwidth arises from the phase and amplitude coupling which gives a wider locking bandwidth for negative detuning in factor of $(1+\alpha^2)^{1/2}$ for a given injection power [12-13]. The more asymmetric the slopes are, the larger the LEF. The ratio of the two slopes of locking bandwidth is power independent and is used to calculate LEF [14].

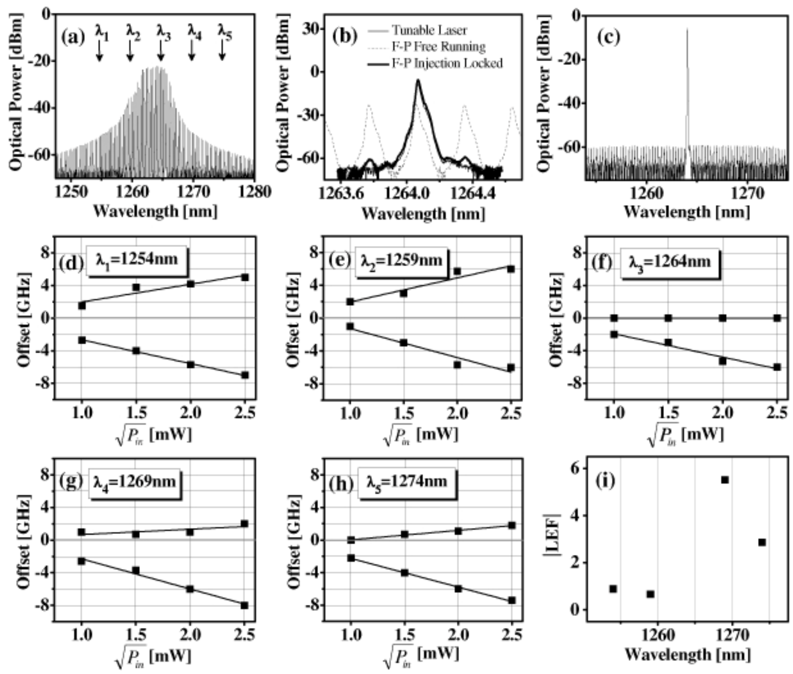

Fig. 1. (a) Optical spectrum of a free running QD F-P laser biased at 45 mA (5 arrows indicate measurement points for LEF), (b) Optical spectra of QD F-P laser before and after injection locking, (c) wide span optical spectrum of injection locked QD F-P laser, (d) ~ (h) injection locking bandwidth with different lasing spectral points, and (i) LEF as function of wavelength.

In Fig. 1 (i), an absolute value of LEF is used since the sign of LEF could not be determined by the injection locking method. It is found that a considerable spectral dependence of the LEF above threshold is observed within ~ 20 nm rather than photon energy dependence or independence of the LEF under low injection current [6,11]. Even though the LEF around the gain peak cannot be calculated from the locking bandwidth due to the resolution limit of the OSA, it is obvious that its locking bandwidth is most asymmetric with respect to others and the value of LEF is above 6. The LEF is significantly reduced (around 1) on the anti-Stokes side and also apparently reduced (around 4) on the Stokes side compared to the LEF around the peak gain. The observed low LEF above threshold on the anti-Stokes side

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is in agreement with theoretical work by Oksanen et al [10]. Oksanen et al predict that due to the shape of density of states, a low LEF can be achieved by detuning the laser operation to shorter wavelengths from the gain maximum, which is red shifted from the density of states maximum due to Fermi-Dirac statistics. The lower LEF on the Stokes side is not clearly understood and needs additional study, however the carrier induced refractive index change on the Stokes side may play a role and will be discussed in the following section.

2.2 Spectral dependence of pulse duration and chirp

In a hybrid or passive mode-locked semiconductor laser, the nonlinearity of the semiconductor gain medium also plays an important role as a pulse broadening mechanism. It was demonstrated that if the optical pulse duration is longer than carrier cooling time, the time varying refractive index due to carrier depletion in semiconductor gain medium introduces temporal cubic phase which modifies the instantaneous frequency $(\omega_{inst} \propto -\partial\phi / \partial t)$, producing a parabolic frequency sweep due to self-phase modulation. The saturable absorber, which removes the leading part of the pulse, and the group velocity dispersion lead to a dominant linear chirp [17-18].

The pulse width and linear chirp are investigated for optical pulses formed through different spectral regimes of QD lasers because LEF affects the pulse broadening mechanism through the carrier induced refractive index change that changes the carrier wavelength versus time. To investigate the spectral dependence of the pulse width and linear chirp, a grating coupled external cavity mode-locked laser is employed to generate optical pulses from five different spectral regimes (1260 nm to 1285 nm) [19]. Passive mode-locking is performed on the cavity whose fundamental cavity frequency is 2.5 GHz with an injection current of 140 mA and reverse bias of 5 V. The threshold current of the laser cavity is ~ 100 mA and the peak amplified spontaneous emission (ASE) from the curved two-section device is centered at 1275 nm with an injection current of 140 mA to the gain section. The optical pulse train is amplified through a 3 mm long QD SOA and diagnosed in terms of optical spectrum, pulse width, and linear chirp. The center lasing wavelength is tuned by only changing the angle of the grating while mode-locking conditions, i.e., injection current and reverse bias, are kept unchanged. Figure 2 shows the optical spectrum, pulse width, and magnitude of linear chirp.

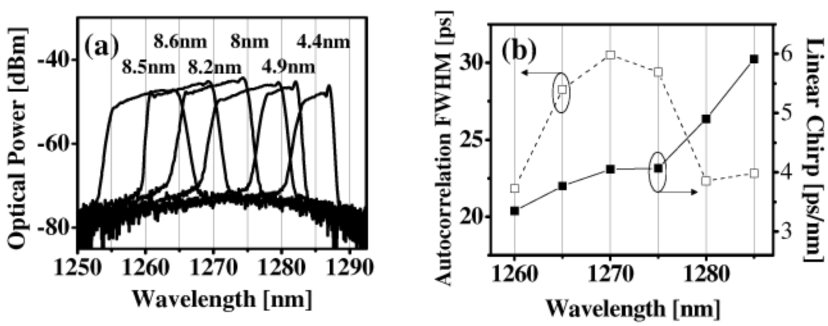

Fig. 2. (a) Optical spectra and (b) autocorrelation FWHM and linear chirp with respect to five different lasing spectral points.

A 3 dB lasing bandwidth of ~ 8.3 nm is measured on the anti-Stokes side (from 1260 nm to 1275 nm), whereas a maximum 3 dB lasing bandwidth of ~ 4.6 nm is measured on the Stokes side (from 1280 nm to 1285 nm) under the same fixed operating conditions. Due to band filling effects the laser has a wider tuning range on the anti-Stokes side. The output pulse duration is apparently reduced on both the anti-Stokes and Stokes side. This behavior is very similar with the LEF measurement of the QD F-P laser, but it should be noted that the output spectral bandwidths from the anti-Stokes and Stokes side are different. It is clear that the pulse duration is reduced when the center lasing wavelength of the mode-locked laser is

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tuned to the anti-Stokes side from the peak of the ASE whereas the output pulse duration from the Stokes side does not show a distinctive spectral dependence. The magnitude of the linear chirp impressed on the mode locked pulses is calculated from the maximum compression position in a dual grating compressor [20]. All pulses are compressed by adding negative group velocity dispersion, which means that all pulses are upchirped regardless of the spectral regimes. It is found that magnitude of linear chirp is smaller on the anti-Stokes side and larger on the Stokes side for pulses formed. This implies that the carrier induced refractive index change of QD lasers is smaller on the anti-Stokes side and contribute to a smaller LEF on the anti-Stokes side as result. Effects from the excited states and inhomogeneous broadening of the QD laser may also contribute to these results [9–11]. A larger linear chirp is observed on pulses on the Stokes side. Since LEF is defined as the ratio between the carrier induced refractive index changes and the differential gain, we believe the low LEF observed from the QD F-P laser on the Stokes side may be due to a relatively higher differential gain value. It should be noted that several curved two-section devices fabricated from different QD wafers were tested under the same operating condition in which the injection current and reverse bias were fixed during passive mode-locking. Consistent and similar results, i.e., shorter pulse widths and less linear chirp from the anti-Stokes side were observed.

3. Conclusion

In conclusion, the spectral dependence of the LEF, the pulse duration and linear chirp when QD lasers oscillate above threshold are observed. The LEF, pulse width and linear chirp are lower on the anti-Stokes side (around 10 nm to 15 nm blue shift from the peak of the gain), however pulses formed on the Stokes side (around up to 10 nm red shift from the peak of the gain) possess relatively large linear chirp. These experimental results suggest that QD lasers which operate on the anti-Stokes side of the gain peak, corresponding to a low nonlinear spectral regime, could potentially achieve lower chirp and shorter optical pulses.

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