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**THE WORLD'S RESOURCE FOR
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Pulse generation and compression via ground and excited states from a grating coupled passively mode-locked quantum dot two-section diode laser

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The authors generate and compress short pulses via the ground and excited state transitions from a passively mode-locked grating coupled quantum dot two-section diode laser at a repetition rate of 2.7 GHz. The selection and isolation of either the ground state or excited state transition were performed by an angle tuning of the grating. The externally compressed pulse widths are 970 fs from the ground state and 1.2 ps from the excited state transition. The sign of the chirp is up chirped for both state transitions. © 2006 American Institute of Physics. [DOI: 10.1063/1.2410217]

Semiconductor diode lasers based on self-assembled quantum dots have attracted strong attention due to predicted superior features of quantum dot over quantum well, such as lower temperature dependence of the threshold current,^{1,2} increased material and differential gain,^{3,4} high bandwidth modulation,⁵ and low chirp.⁶

Mode locking of quantum dot semiconductor diode lasers has been widely performed. High average power, ultrafast pulses and up chirped pulses were reported from monolithic or external cavity lasers via the ground state transition.^{7–10} The quantum dot excited state transitions possess interesting characteristics such as ultrafast gain recovery, higher differential gain, and negative linewidth enhancement factor.^{11,12} Also, quantum dot semiconductor lasers do not exhibit gain clamping in the excited state transition after the lasing threshold of the ground state due to a combination of finite intraband relaxation time and limited density of states. The so-called phonon-bottleneck effect causes simultaneous two-state lasing or abrupt blueshift to the excited state from the ground state as the injected current increases. These lasing behaviors are dependent on the cavity length.^{13,14} The expansion of bandwidth using ground and excited state transitions makes a quantum dot mode-locked diode laser suitable as a two band clock recovery source for telecommunication applications. Excited state mode locking was demonstrated first from monolithic two-section diode laser by control of the injection current and reverse biases to force lasing to switch from the ground state to the excited state transition.¹⁵

In this letter, we study the pulse characteristics of quantum dot (QD) based mode-locked lasers operating exclusively on the ground state (GS) and the excited state (ES) transitions, in terms of pulse duration and chirp's sign and magnitude. Switching of the lasing wavelength between the GS and ES transitions was controlled by an external optical feedback using a grating which prevents the lasing competition between both states and also achieves stable ES mode locking with reduced injection currents and reverse bias. In addition, isolation and independent selection of the ES and GS mode-locking regimes also allow the independent study

of the pulse forming and nonlinear dynamics of each state, independently.

For this experiment, a curved two-section device and a semiconductor optical amplifier (SOA) were fabricated with a ridge-waveguide structure from a QD wafer whose active region is formed by ten layers of InAs quantum dots covered by an InGaAs quantum well.¹⁶ The QD two-section device length and waveguide width are 2 mm and 4 μm , respectively. The length of the saturable absorber is 250 μm . The gain section is curved with an angle of 7° and tapered at termination to minimize the back reflection from the facet.¹⁷ The waveguide of the QD SOA is also 7° tilted and has 1.8 mm length. No high-reflection or antireflection coating was applied onto these devices. Neither the two-section device nor the SOA exhibited any noticeable Fabry-Pérot modulation, even at high injection currents. An external cavity with a fundamental frequency of 2.7 GHz using the QD two-section device and a grating (300 lines/mm) was constructed and the output from the gain section was focused on the grating in the Littrow configuration. Stable passive mode locking of GS and ES were obtained at dc currents of 140 and 240 mA with reverse biases of ~ 5 and ~ 2 V, respec-

FIG. 1. ES mode-locked optical spectrum. Left inset: Wide span ES mode-locked optical spectrum. Right inset: GS mode-locked optical spectrum.

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FIG. 2. Experimental setup for pulse compression. I, isolator; QD SOA, quantum dot semiconductor optical amplifier.

tively. Figure 1 shows the optical spectrum of the generated pulse trains. Lasing from the ES transition has over 28 dB suppression of the GS amplified spontaneous emission as shown in left inset of Fig. 1. It rules out any participation from the ground state transition. The lasing wavelengths from the GS and ES transitions are 1275 and 1193 nm with 3 dB optical bandwidth of 6 and 4.25 nm, respectively. Selection of either the GS or ES transitions was achieved by changing the angle of the grating. The 1.8-mm-long QD SOA was used to amplify the pulses to measure the intensity autocorrelation signal. Pulses from the grating coupled mode-locked QD two-section diode laser were measured to be 14 ps with a time-bandwidth product (TBP) of 15.5 via the GS transition and 10.8 ps with a TBP of 9.7 via the ES transition, assuming a hyperbolic-secant-squared pulse shape. Large TBPs of pulses via the GS and ES transitions suggest that both pulses generated from the grating coupled mode-locked QD two-section diode laser are highly chirped.

Pulse trains were sent to the dual grating dispersion compensator to compress pulses and to investigate chirp sign. Figure 2 shows the experimental setup for pulse compression. An internal telescope configuration allows the compressor to access negative or positive group velocity dispersion region by moving the second grating from the zero dispersion position.¹⁸ Both pulses from the GS and ES transitions are maximally compressed in the negative group velocity dispersion region, which shows that pulses generated via the ES transition are also up chirped, similar to generated pulses via the GS transition.¹⁰ The compressed pulse width versus applied dispersion (grating position) is plotted in Fig. 3(a) for ES. The inset shows the same plot for GS. It should be noted that ES requires more dispersion (large displacement) as compared to GS. Also the rate of pulse broadening versus applied dispersion is large for GS owing to the larger lasing bandwidth. The minimum compressed pulse widths are 970 fs with a TBP of 1.1 for the GS transition and 1.2 ps with a TBP of 1.1 for the ES transition, assuming a hyperbolic-secant-squared pulse shape. The intensity autocorrelation signal of the compressed pulses is shown in Fig. 3(b) with the GS autocorrelation shown in the inset. Figure 4 shows generated pulse characteristics via the GS and ES transitions in terms of pulse widths and magnitude of possessed linear chirp with respect to the reverse bias applied on the saturable absorber. The magnitude of the linear chirp is converted from the maximally compressed position of the second grating in the compressor using the following relationship:¹⁸

$$D = \frac{\omega}{\lambda l_e} \frac{d^2 \phi}{d\omega^2}, \quad (1)$$

(a)

(b)

FIG. 3. (a) Pulse width variation from ES transition vs the second grating position. Inset: Pulse width variation from GS transition vs the second grating position. (b) Autocorrelation signal of compressed pulses from ES transition. Inset: Autocorrelation signal of compressed pulses from GS transition.

$$\frac{d^2 \phi}{d\omega^2} = -\frac{\lambda^3}{2\pi c^2 d^2 \cos^2 \theta} l_e, \quad (2)$$

where D is the dispersion parameter (ps/nm cm), $d^2 \phi / d\omega^2$ is the group velocity dispersion, l_e is twice the second grating

FIG. 4. Pulse widths and possessed linear chirp magnitude vs reverse bias voltage.

distance from zero dispersion point, d is the groove spacing, and θ is the emerging angle. The large linear chirp and TBPs over three times the Fourier-transformed limit after compression imply that linewidth enhancement factor of pulses via GS and ES transitions is similar to that of quantum well mode-locked lasers.

In conclusion, we generate stable optical pulse trains via isolating both GS and ES transitions from a grating coupled passively mode-locked QD two-section diode laser. Isolation of the ES and GS mode-locking regimes allows for independent study of each state, independently. The pulses generated from the GS and ES transitions are compressed and the minimum compressed pulse widths are 970 fs and 1.2 ps, respectively. The sign of the chirp of the generated pulses via the GS and ES transitions is similar and is up chirped.

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