THz optical pulses from a coupled-cavity quantum-dot laser

J. Liu [a],*, Z.G. Lu [a], P.J. Poole [a], P.J. Barrios [a], D. Poitras [a], Z. Jiao [a,b], X.P. Zhang [b]

[a] *Institute for Microstructural Sciences, National Research Council Canada, 1200 Montreal Road, Ottawa, Canada K1A 0R6*
[b] *Department of Electrical and Computer Engineering, Concordia University, Montreal, Canada H3G 1M8*

ARTICLE INFO

ABSTRACT

Optical pulses are generated from a coupled-cavity quantum-dot (QD) laser consisting of a short QD-waveguide Fabry–Perot (F–P) cavity and three long external fiber Bragg grating (FBG) cavities. When the laser is biased at low operation current, the feedback from the external cavities dominates and laser pulses have a 1.01 THz repetition rate, determined by the equal frequency difference of the three FBGs. We are thus able to decouple the repetition rate of a mode-locked laser from the cavity length. With much higher bias current, the QD F–P cavity dominates and the repetition rate is switched to 43.8 GHz, defined by the length of the F–P cavity.

Crown Copyright © 2011 Published by Elsevier B.V. All rights reserved.

1. Introduction

Since the first demonstration in 2001 [1], passive mode-locking of quantum-dot (QD) lasers has attracted much more attention [2–4]. Due to the broadband gain [5] and fast carrier dynamics [6] of QDs, the resulting lasers are excellent candidates for mode-locking, capable of generating optical pulses with pulse durations down to 312 fs [7] and high repetition rates up to 346 GHz [8]. In order to scale the repetition rate up to the THz range using conventional cavity geometries, the length of the optical cavity must be shrunk to less than 50 μm. In general this is too short to provide enough gain for lasing and mode-locking. To solve this problem a novel coupled-cavity configuration without saturable absorber was investigated. It consisted of a 1 mm InAs/InP QD Fabry–Perot (F–P) cavity coupled to three external fiber Bragg grating (FBGs) cavities acting as end cavity mirrors. Without the external cavities in place, the QD F–P cavity laser emits a frequency comb with a longitudinal mode spacing of 43.8 GHz, producing pulses at that same frequency. The three external FBG cavities select three equally spaced modes from the frequency comb, feeding them back to the F–P cavity. This suppresses the other longitudinal modes of the laser F–P cavity. Once these three selected modes have sufficient intensity, and the dispersion over the lasing bandwidth is small enough to initiate four-wave mixing (FWM) within the QD F–P cavity gain section, mode-locking with the repetition rate defined by FBGs can be realized [3]. This proposed scheme is quite different from that of the mode-locked laser (MLL) with spatially separate gain media [9], but both offer routes to mode-locked lasers with a flexible repetition rate up to the THz range and a dynamically controlled bandwidth. Such high repetition-rate MLLs are expected to find applications in telecommunications, THz clocking, and THz radiation generation [10].

2. Experimental results and discussion

The experiment setup is shown in Fig. 1. The QD F–P laser used for these experiments was a ridge waveguide laser with a 3 μm ridge width and a 1 mm cavity length defined by cleaved facets. One facet (M1) was coated for broadband high reflectivity (95%); the other (M2) was as cleaved giving a 31% reflectivity. The gain medium consisted of five stacked layers of InAs QDs with InGaAsP barriers [11]. It was driven with continuous-wave (c.w.) current on a temperature-controlled heat sink. Its output was coupled through a lensed and coated fiber to the left 90% port of an optical coupler. The right 90% port of the same coupler was connected to a polarization controller through to three FBGs written in series in a single piece of fiber to form three external fiber cavities with different cavity lengths of about 8.6–8.7 m. The right 10% port was used for measurements; all other unused ports were properly terminated to avoid back-reflections.

The optical transmission spectrum of the three FBGs in series is shown in Fig. 2(a). Their central Bragg wavelengths are 1531.868 nm, 1539.656 nm, and 1547.506 nm respectively, with peak reflectivities of 96% and full width at half maxima of 0.080 nm. The inter-FBG frequency spacing is approximately 1.01 THz. These external fiber cavities only feed back to the QD gain medium the longitudinal modes emitted from the QD F–P laser whose wavelengths fall within the reflecting bands of the FBGs; the rest are transmitted. The selected modes could be optimized in terms of amplitude and wavelength by adjusting the

* Corresponding author. Tel.: +1 613 9916839; fax: +1 613 9930755.
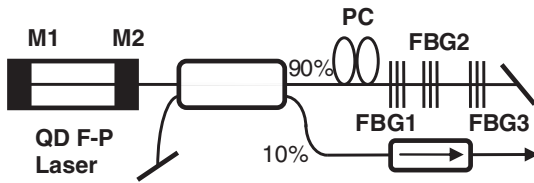*E-mail address:* jiaren.liu@nrc.ca (J. Liu).

Fig. 3. Four wave mixing signals observed at a bias current of 47 mA.

QD laser bias current or temperature to shift the frequency comb of the QD F–P laser. Due to the reduction in optical loss of the whole system at the FBG back-reflection wavelengths, the coupled-cavity laser can lase at a bias current below that of the bare QD F–P device, 48 mA.

For example, Fig. 2(b) shows the lasing spectrum for a bias of 45 mA. The spectrum is dominated by three lasing modes at 1531.827 nm, 1539.655 nm and 1547.548 nm respectively. These correspond to the reflectivity peaks of the FBGs. The resulting pulse train with a pulse period of about 1.0 ps, as shown in Fig. 2(c), was measured and averaged over 64 times with an intensity autocorrelator. Its repetition rate and pulse duration are 1.01 THz and 0.5 ps, respectively. Due to the intensity or amplitude difference of the three lasing modes, the c.w. background of the laser pulses is high so that the pulse contrast is poor. The above results indicate that the external fiber cavities are controlling the lasing spectrum at low bias current, and that the three lasing modes are phase-correlated. This correlation is likely mediated through the strong FWM observed in QD gain media [12]. The FWM was examined more carefully at a low bias current. By setting the drive current to 47 mA and tuning the temperature the coupled-cavity laser could be made to operate on only two of the FBG-selected modes (the other FBG peak was mismatched from any longitudinal mode of the QD F–P laser). FWM Stokes and anti-Stokes signals, labeled by the arrows in Fig. 3, were
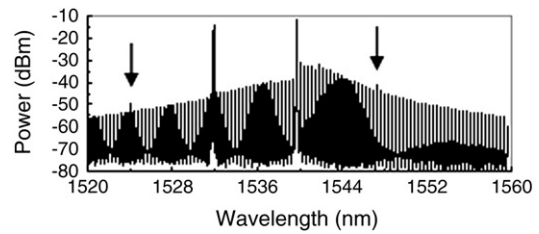
clearly observed at the wavelengths of 1547.5 nm and 1524.1 nm. By changing the frequency spacing and the number of FBG sets, laser pulses with different repetition-rates, bandwidth, and pulse duration could be produced, independent of the original QD F–P cavity length [9]. The physical limitations on the high pulse repetition rate are whether the QD gain medium exhibits carrier dynamics fast enough to sustain successive pulse emission, and the efficiency of the FWM process.

Next we consider the lasing behavior of the coupled-cavity QD laser at high bias current. In this operating regime the laser itself was lasing with tens of longitudinal modes simultaneously with the three modes enhanced by the feedback from the FBGs. This resulted in a comb of modes with a 43.8 GHz mode spacing and three dominant modes with a 1.01 THz spacing. This is shown in the inset of Fig. 4(c). Consequently, the envelope of 1.01 THz pulse train was modulated at a frequency of 43.8 GHz, with the modulation depths dependent on the weighting of the lasing modes. As the bias current was increased the modulation depth also increased, as shown in Fig. 4. When the coupled-cavity laser was biased at a current of 175 mA the pulse train was dominated by pulses with a duration of
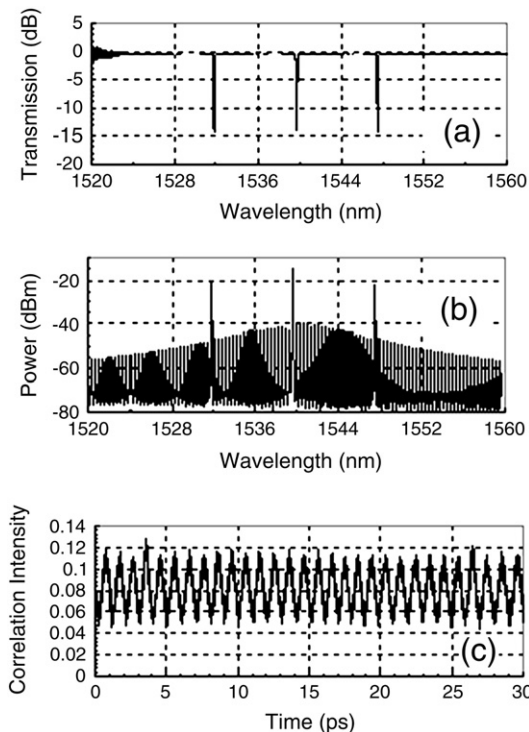

Fig. 2. (a) Transmission spectrum of the three FBGs. (b) Lasing spectrum of the coupled-cavity QD laser at a bias current of 45 mA. (c) Pulse train indicating the repetition rate of 1.01 THz.
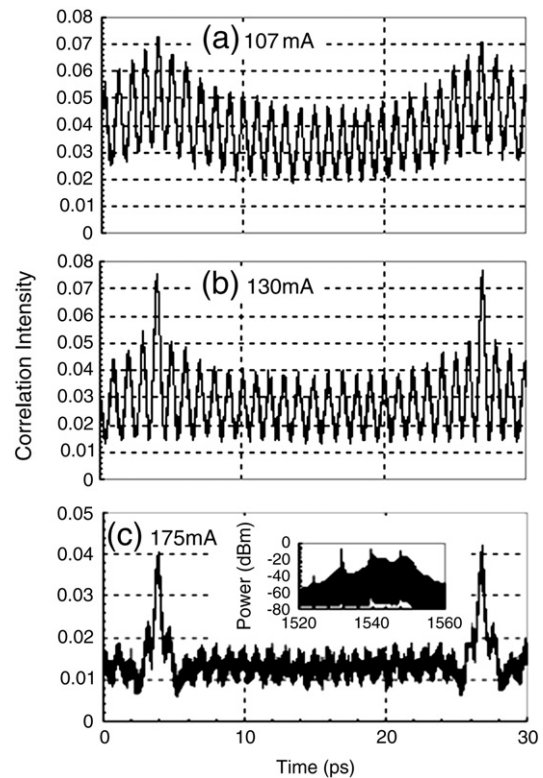

Fig. 4. Autocorrelation traces of the QD coupled-cavity laser biased at (a) 107 mA, (b) 130 mA, and (c) 175 mA, respectively. Inset in (c): the corresponding optical spectrum at 175 mA.

less than 0.5 ps at a repetition rate of 43.8 GHz. A residual modulation at 1.01 THz could still be observed. Since at higher drive currents more lasing modes participated in the Fourier synthesis of the pulse trains [13], the c.w. background was significantly decreased and the pulse contrast was higher. Notice that the pulse duration for the 43.8 GHz pulses train shown in Fig. 4(c) could be narrowed due to the modulation at a THz frequency [14].

3. Conclusion

In conclusion, by coupling a QD F–P laser to external FBGs to provide optical feedback at three different wavelengths (separated by 1.01 THz) allowed us to generate a 1.01 THz repetition-rate pulse train. The repetition rate was completely independent of the QD F–P laser cavity length, being controlled through the properties of the FBGs. At high drive current the repetition-rate became dominated by the cavity length of the QD F–P laser, switching to a train of 0.5 ps pulses at 43.8 GHz. This external cavity approach utilizing a QD gain medium has the potential to provide extremely high repetition rate lasers, whose pulse rate, bandwidth, and even pulse duration can be readily tuned through spectrally tailored optical feedback.

References

[1] X. Huang, A. Stintz, H. Li, F. Lester, J. Cheng, K. Malloy, Applied Physics Letters 78 (2001) 2825.
[2] M. Kuntz, G. Fiol, M. Lammlin, D. Bimberg, M. Thompson, K. Tan, C. Marinelli, R. Penty, I. White, V. Ustinov, A. Zhukov, Yu. Shernyakov, A. Kovsh, Applied Physics Letters 85 (2004) 843.
[3] J. Renaudier, R. Brenot, B. Dagens, F. Lelarge, B. Rousseau, F. Poigt, O. Legouezigou, F. Pommereau, A. Accard, P. Gallion, G. Duan, Electronics Letters 41 (2005) 1007.
[4] J. Liu, Z. Lu, S. Raymond, P. Poole, P. Barrios, D. Poitras, Optics Letters 33 (2008) 1702.
[5] A. Kovsh, I. Krestnikov, D. Livshits, S. Mikhrin, J. Weimert, A. Zhukov, Optics Letters 32 (2007) 793.
[6] L. Zhang, T.F. Boggess, D.G. Deppe, D.L. Huffaker, O.B. Shchekin, C. Cao, Applied Physics Letters 76 (2000) 1222.
[7] Z. Lu, J. Liu, P. Poole, P. Barrios, D. Poitras, Optics Express 16 (2008) 10835.
[8] K. Merghem, A. Akrout, A. Martinez, G. Aubin, A. Ramdane, F. Lelarge, G. Duan, Applied Physics Letters 94 (2009) 021107.
[9] R.M. Oldenbeuving, C.J. Lee, P.D. van Voorst, H.L. Offerhaus, K.-J. Boller, Optics Express 18 (2010) 22996.
[10] A. Schwanden, D. Lorenser, H.J. Unold, R. Pschotta, E. Gini, U. Keller, Optics Letters 30 (2005) 272.
[11] P.J. Poole, K. Kaminska, P. Barrios, Z. Lu, J. Liu, Journal of Crystal Growth 311 (2009) 1482.
[12] Z. Lu, J. Liu, S. Raymond, P.J. Poole, P.J. Barrios, D. Poitras, F. Sun, G. Pakulski, P.J. Bock, T.J. Hall, Electronics Letters 42 (2006) 1112.
[13] H.A. Haus, IEEE Journal on Selected Topics in Quantum Electronics 1173 (2000).
[14] C. Mesaritakis, C. Simos, H. Simos, S. Mikroulis, L. Krestnikov, D. Syvridis, Applied Physics Letters 96 (2010) 211110.