Automatic Cross Carrier-Envelope Phase Locking Within a Dual-Peak Mode-Locked Quantum-Dot Diode Laser

Jiaren Liu, Zhenguo Lu, Philip J. Poole, Pedro J. Barrios, and Daniel Poitras

***Abstract*—We demonstrated automatic cross carrier-envelope phase locking between two synchronized pulse trains at different wavelengths generated within a single InAs/InP quantum-dot diode laser cavity. The resulting waveforms, verified by optical auto-/cross-correlation and explained by a theoretical model, show multipeaks or quasi-periodic subpulses with a central-subpulse pulse duration of about 183 fs.**

***Index Terms*—Mode-locked lasers, quantum dot, carrier-envelope phase locking, semiconductor lasers.**

I. Introduction

FOR a mode-locked laser, the relative phase of the carrier wave with respect to the envelope of the ultrafast pulse train is referred to as the carrier envelope phase (CEP). It is typically a constant phase slip from pulse to pulse determined by the difference between group and phase velocities within a mode-locked laser cavity. Since the first CEP stabilization was demonstrated at the turn of the century, it has played critical roles in atto-second science [1]–[3] and optical clock work [4]–[5]. The CEP locking was experimentally implemented by using the self-referencing technique and the feedback loop [6]. The similar concepts and techniques were also extended to coherently cross-locking of two independent mode-locked lasers [7] and chirped-pulse amplification [8]–[12]. As CEP locking technique evolves and is advanced, it has found many interesting applications in arbitrary pulse synthesis [13]–[15] and quantum optics [16]. In this paper, we report on the observation of automatically cross-CEP locking within a dual-peak mode-locked quantum-dot (QD) diode laser.

II. Theory

When a mode-locked QD diode laser [17]–[20] emits two ultrafast pulse trains, labeled by the different carrier frequencies $\omega_{c,j}$ where $(j = 1, 2)$ the amplitude of the whole laser field [6], [15] for the *n*th pulse is

$$E(t) = \sum_{j=1}^{2} A_j(t - nT_j - T_{0,j}) .\mathrm{Cos}(\omega_{c,j}t - n\omega_{c,j}T_j + n\Delta\Phi_{CE,j} + \Phi_{0,j}) \quad (1)$$

where $T_j, T_{0,j}, \Delta\Phi_{CE,j}$, and $\Phi_{0,j}$ are the pulse period, the pulse envelope-offset time, the pulse-to-pulse CEP, and the carrier-offset phase respectively while $A_j(t)$ denotes the slowly-varying electric-field amplitude envelope, all for the *j*th pulse train.

When $T_1 = T_2 = T$, two pulse trains at different central carrier frequencies from the same Fabry-Perot (F-P) laser with a cavity length of L have the equal temporal period determined by $T = 2n_g(\omega_{c,j})L/c$, requiring the same group refractive index at different carrier frequencies $n_g(\omega_{c,1}) = n_g(\omega_{c,2})$. Further, the synchronization of the two pulse trains requires $T_{0,1} = T_{0,2} = T_0$ so that any *n*th pulse in one pulse train is temporally overlapped over with, and becomes indistinguishable from the *n*th pulse of another pulse train. If these conditions are true then only one train is observable. Furthermore, if the cross CEP locking condition is held true then

$$(\omega_{c,1} - \omega_{c,2})T + \Delta\Phi_{CE,1} - \Delta\Phi_{CE,2} = 2\pi q \quad (2)$$

where q is an integer, the intensity of the laser field for the *n*th pulse in this observable pulse train detected by a slow detector (i.e., neglecting the high-frequency components) can be written as:

$$I(t) \propto \sum_{j=1}^{2} I_j(t - nT - T_0) + 2\mathrm{Cos}(\Delta\omega_c t + \Delta\Phi_0) \prod_{j=1}^{2} A_j(t - nT - T_0) \quad (3)$$

where $\Delta\Phi_0 = \Phi_{0,1} - \Phi_{0,2}$ is the difference of two carrier-offset phases. Eq. (3) indicates that beating notes at the frequency $\Delta\omega_c = \omega_{c,1} - \omega_{c,2}$ are reproduced for all pulses of this undistinguishable pulse train. The waveform of each resulting pulse thus consists of several sub-pulses with a shorter duration than that of the constituent pulses at the two carrier frequencies. These sub-pulses have a period of about $2\pi/\Delta\omega_c$. To observe the sub-pulse structure in the *auto*-correlation only requires that the two pulse trains have the same period and are overlapped in time, their relative carrier–offset phase and/or pulse-to-pulse CEP is not important. On the other hand to observe identical sub-pulse

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structure in the *cross*-correlation peaks, as seen in our measurements later, requires that this sub-pulse structure is identical from pulse to pulse. This is only the case if the two original pulse trains shown in Eq. (1) meet the conditions of the cross-CEP locking in Eq. (2), and have the fixed difference of the carrier-offset phases $\Delta\Phi_0$. We must emphasize that Eq. (2) represents the cross CEP locking $\Delta\Phi_{CE,1} - \Delta\Phi_{CE,2}$ of two original pulse trains at different carrier frequencies other than the self CEP locking $\Delta\Phi_{CE,j}$ of each original pulse train as discussed elsewhere. The observation of the identical and repeated beat notes within the pulse envelopes as predicted in Eq. (3) is strong evidence of the extended cross CEP locking. If the Eq. (2) is not met, the *n*th pulse of this pulse train in Eq. (3) will have the phase jump with respect to the *(n + 1)*th pulse so that the resulting sub-pulse waveform will be changed from one pulse to another. Additionally, if $\Delta\Phi_0$ is completely and/or partially random other than constant, the averaging over the pulse trace shall smear the beating notes at the frequency $\Delta\omega_c$.

III. Experimental Results

The laser used in this study was similar to that described in Ref. [17]. It was an InP-based quantum dot Fabry-Perot semiconductor laser with ridge waveguide width of 3 μm and cavity length of 858 μm. The gain medium consisted of five stacked layers of InAs QDs with InGaAsP barriers. One of the end mirrors was left as cleaved (~31% reflectivity) serving as the output coupler and another was coated to provide a flat broadband reflectivity of 98%. The laser was tested with continuous-wave (CW) injection current on a temperature-controlled heat sink. Its output was coupled to a lensed AR-coated fiber and measured by an optical spectrum analyzer and a fiber-based intensity auto-/cross-correlator, respectively.

Fig. 1 shows the lasing spectra for the bias currents of 100 mA (with a central frequency of about 195 THz) and 200 mA (with the dual central frequencies of about 194 THz and 196 THz). From the laser threshold of 56 mA up to 115 mA, the lasing spectra are contained within a single peaked envelope. As the bias current goes beyond 115 mA, the lasing spectral envelope splits and dual-peaked partially-symmetric structures are clearly observed, with increasing separation as the drive current increases. The spectral spacing of two peaks at 200 mA in Fig. 1(b) is closed to 2.3 THz. The spectrally separated emission features can be considered as coming from two different pulse trains within the same laser cavity. The mechanism of dual-wavelength mode-locking operation is physically originated from ground and excited states lasing for 1.3 μm QDs [17]. But it is not yet fully understood for 1.5 μm QDs without excited state lasing. As we discussed in Ref. [13], it could be explained by giant Rabi splitting induced by interaction of laser pulses with QDs inside a very small waveguide.

Fig. 2 shows the experimental auto-/cross- correlation traces for the laser drive current used in Fig. 1. The pulse repetition rate is about 50 GHz (corresponding to the pulse round trip frequency of a cavity of length 858 μm) with a pulse duration of approximately 1 ps. At the bias of 200 mA, each pulse in

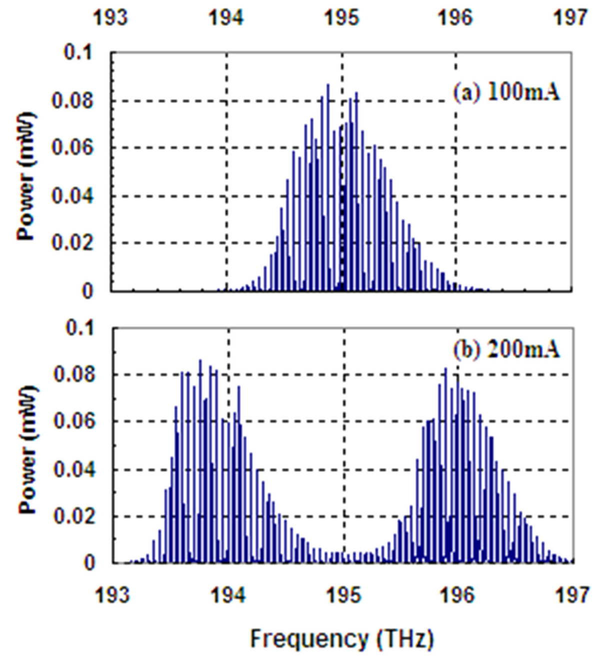

Fig. 1. Optical spectra of a InAs/InP QD laser biased at the currents of (a) 100 mA and (b) 200 mA, respectively.

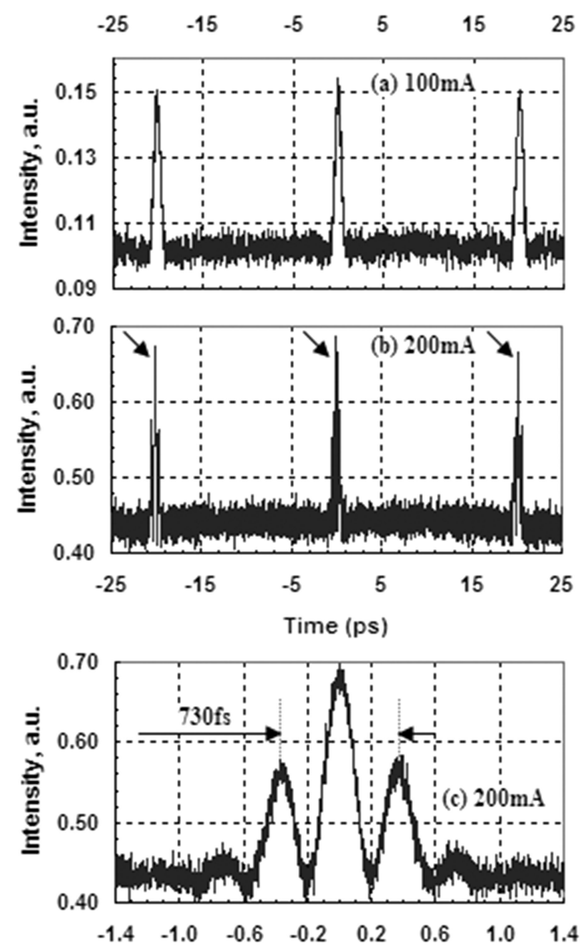

Fig. 2. Pulse trains at the bias currents of (a) 100 mA and (b) 200 mA respectively as well as zoom-in sub-pulses of a single pulse envelope at 200 mA.

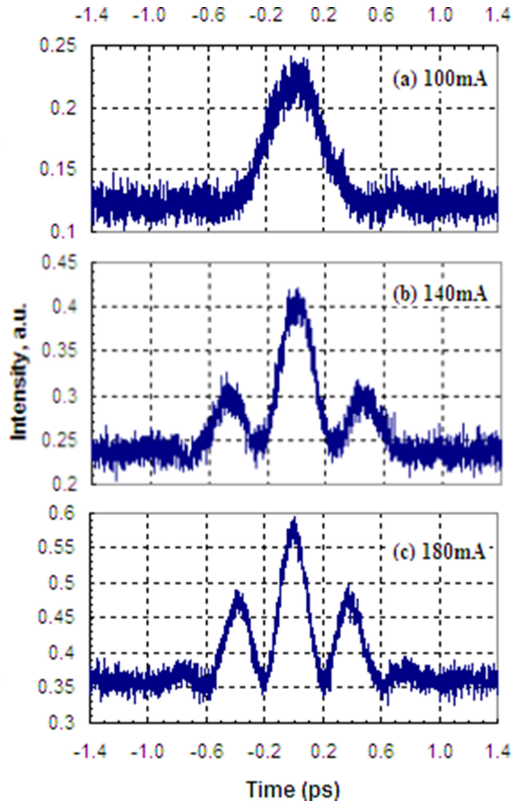

Fig. 3. Zoom-in single original pulse waveforms at the bias currents of (a) 100 mA, (b) 140 mA, and (c) 180 mA, respectively.

the train contains identical quasi-periodic sub-pulses which are clearly and repeatedly observed for all pulses in the pulse train, shown in more detail in Fig. 2(c) where 64-time averaging of the pulse waveforms is used to exclude the possible randomness of $\Delta\Phi_0$. The experimental data shown in Fig. 2 is consistent with the above theoretical prediction in Eqs. (2) and (3) for cross CEP locking. To this end, we conclude that the original pulse trains labeled by different carrier frequencies in Fig. 1(b) and generated by a F-P cavity diode laser have the same repetition rate, are synchronized and their CEPs are automatically and crossly locked together.

The central subpulse of any pulse in the undistinguishable train is about 365 fs away from the adjacent subpulses, as shown in Fig. 2(c), so that the pulse duration of the central subpulse is estimated to be 183 fs. Notice that 365 fs $\times$ 2.3 THz $\neq$ 1. This imperfection is believed to originate from the effects of pulse envelopes in Eq. (3) on the periods of subpulses. For further confirmation of the automatic cross-CEP locking, the pulse envelopes at the bias of 140 mA and 180 mA are also measured as shown in Fig. 3. The periods of subpulses at 140 mA, 180 mA, and 200 mA are 476 fs, 386 fs and 365 fs, respectively. The higher the bias currents are, the smaller the periods of sub-pulses and the bigger the corresponding spectral splitting of dual peaks.

A large DC background in Figs. 2 and 3 is big concern in general mode-locking. In order to clarify this issue, each of these dual peaks was filtered out and studied experimentally. We found that two filtered pulse trains with different carrier frequencies in Fig. 1(b) have the exactly same repetition rate

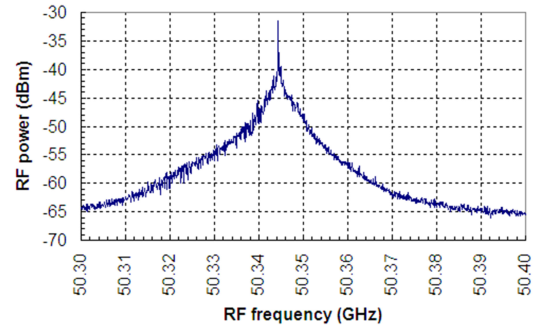

Fig. 4. RF beating frequency of 50.343 GHz with the 3-dB bandwidth of less than 200 KHz.

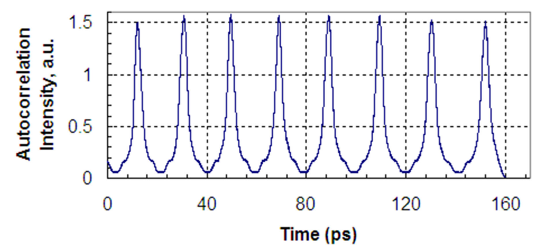

Fig. 5. Auto-/cross-correlated pulse train for the 8 central lasing modes filtered out from the left-hand peak in Fig. 1(b) with optical signal amplification and DC background calibration.

of 50.343 GHz as shown in Fig. 4, but no sub-pulse structures within their pulse envelopes were observed as measured with the auto-/cross-correlator. Their 3-dB bandwidths of RF beating signals, less than 200 KHz, are small enough to indicate mode-locking. Furthermore by narrowing the optical filter bandwidth, optimizing its center frequency, and selecting only 8 central lasing modes out from the left-hand peak in Fig. 1(b), the corresponding pulse extinction rate was measured to be 30:1, as shown in Fig. 5. These results indicate that a two pulse trains with different carrier frequencies in Fig. 1(b) did be mode-locked and the large DC background in Figs. 2 and 3 was mainly due to non-lasing modes outsides the lasing bands and partially mode-locked lasing modes located at the edges of the lasing bands. Additionally, pulse intensity difference and randomness of $\Delta\Phi_0$ between two original pulse trains in Eq. (3) have only minor effects on the DC backgrounds because subpulse troughs have the same height as pulse-to-pulse DC background in Fig. 2(b).

In conclusion, automatically cross CEP locking within a dual-peak mode-locked quantum-dot diode laser was experimentally observed and theoretically explained with a simple model for the first time. The pulse duration of the central subpulse down to 183 fs was demonstrated. This type of cross CEP locking at tens of GHz with a simple diode laser can find many meaningful applications in terahertz wave sources [21], ultrahigh repetition-rate optical clock [22], and shorter optical pulse generation.

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