40 GHz mode-beating with 8 Hz linewidth and 64 fs timing jitter from a synchronized mode-locked quantum-dash laser diode

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Linewidth narrowing of the radio frequency beat-tones and the optical-modes is experimentally investigated in a ~40 GHz quantum-dash mode-locked laser diode subject to optical injection of 10 GHz pulses. In comparison to the 75 kHz linewidth exhibited by the beat-tones in passive mode-locking conditions, a remarkable reduction to less than 8 Hz is achieved when the laser is under optical injection. From this beat-tone signal, an integrated root-mean-square timing jitter of 64 fs is calculated. In addition, a quadratic profile of the optical linewidth with the wavelength is observed in active locking, reaching a minimum of 1:7 MHz for the longitudinal modes around 1530 nm and progressively increasing to 37:4 MHz for modes at 1525 nm.

Owing to their fast carrier dynamics and broad gain spectrum, semiconductor mode-locked laser diodes (MLLD) based on two-section quantum-dots (QD) and single-section quantum-dash (QDash) structures have attracted a considerable interest for the variety of their applications in optical communications. For instance, using two-section QD mode-locked lasers, high power pulses at 21 GHz featuring a full-width at half-maximum (FWHM) in the sub-ps regime [1], as well as 10 GHz electrical signals exhibiting a sub-kHz linewidth [2] have been reported. Similarly, a linewidth narrowing of the beat-tones (from 500 Hz down to 40 Hz) has been accomplished in 10 GHz hybridly mode-locked QD lasers by injecting a sinusoidal electrical signal into the absorber section [2]. Using single-section devices, generation of short-pulses at repetition rates from 40 GHz [3] to 346 GHz [4], as well as frequency multiplication at 270 GHz [5] have been demonstrated by passively mode-locked QDash Fabry– Pérot (FP) laser diodes. In active mode-locking regime, all-optical frequency down-conversion clock-recovery up to 425 GHz has been experimentally investigated by 42 GHz single-section QDash lasers [6]. Moreover, implementing an optical self-injection loop, a 10 GHz low phase-noise all-optical oscillator with a linewidth of 200 Hz is reported in single-section QDash FP-MLLD [7]. The aim of this Letter is to experimentally investigate the linewidth narrowing of the beat-tone signals from a mode-locked laser operating under optical injection. From the synchronized mode-beating signals, the integrated timing jitter reduction is addressed. In addition, the impact of the active locking mechanism on the line-widths of the longitudinal-modes is studied.

The device under investigation is a ∼1 mm long, single-section, DC-biased and polarization-dependent QDash Fabry–Pérot laser without a saturable absorber. A detailed description of the QDash-based heterostructure, as well as the dimensions of the active core can be found in [8]. The mode-locked laser presents a bias threshold of 18 mA and an average power of 1:6 mW, collected by a 0:5 NA lensed fibre when operating at 350 mA and temperature controlled at 25 °C. It features over 40 longitudinal-modes with 0:31 nm intermodal separation, resulting in a 3 dB optical bandwidth of 12 nm (1:54 THz) centered at 1526 nm. Despite being DC-biased, this laser generates optical pulses by passive mode-locking at 40 GHz repetition rate over a current range between ∼100 and 450 mA; with a minimum timing jitter of 150 fs [3,9]. In addition, as illustrated in Fig. 1 the central frequency and linewidth of the beat-tones obtained at the output of the QDash MLLD operating in free-running conditions exhibit a tunability of ∼60 MHz and a reduction from ∼75 to 25 kHz with bias current, respectively. Beat-tones are best fitted with a Lorentzian shape for currents within ∼100 to 450 mA.

The experimental setup to measure the optical and beat-tone linewidths of the QDash MLLD operating under optical injection is shown in Fig. 2. A tunable mode-locked laser (TMLL) at 1550 nm driven by an electrical clock is used to generate a train of 1:6 ps pulses at 10 GHz repetition rate. Pulses are amplified with an Erbium-doped fiber amplifier (EDFA), filtered with a 5 nm optical bandpass filter (OBPF-1) for noise suppression and then injected into the QDash ML laser through an optical circulator. Beat-tones from the QDash MLLD are analyzed by using a 50 GHz photo-diode (PD) and an electrical spectrum analyzer (ESA) after filtering out the injected pulses by a 5 nm filter (OBPF-2) centered at ∼1529 nm.

Each longitudinal-mode of the QDash laser is selected by the optical filter OBPF-3. This filter is tunable in both central wavelength and bandwidth. It also features a square bandpass profile with a minimum bandwidth of 0:1 nm. The selected optical-modes are then analyzed by an ESA using a self-heterodyne detection (SHD) setup [10]. An optical spectrum analyzer (OSA) with a resolution of 20 MHz is used for monitoring the optical spectrum at the output of OBPF-3.

The beat-tone signal obtained while the QDash MLLD is biased at 100 mA and synchronized to the optical pulses detailed above is shown in Fig. 3(a) (blue trace). For the sake of the discussion, the beat-tone at the same bias condition while the laser is operating in free-running is shown, too (red trace). Both traces have been recorded setting the ESA at a 50 MHz span and a 10 kHz resolution bandwidth. Two distinctive characteristics are observed. A frequency shift of ∼4:8 MHz, which results from the difference between the central frequency of the beat-tones in passive mode-locking (39:813 GHz) and the frequency of the fourth harmonic component of the injected pulses (39:818 GHz, driven by the signal generator). Most importantly, a remarkable reduction of the FWHM of the beat-tone signal is achieved, changing from ∼75 kHz in free-running to ∼8 Hz under optical injection, at the same bias current and temperature conditions on the laser diode. A detailed view of the retrieved beat-tone in such optical injection conditions is shown in the inset of Fig. 3(a) and has been recorded by setting a 600 Hz span and a 10 Hz resolution bandwidth at the ESA. Indeed, a −10 dB linewidth of ∼24 Hz is measured, which gives a FWHM of ∼8 Hz. In addition, an integrated root-mean-square (rms) timing jitter of ∼64 fs is calculated from the phase-noise power spectral density of the recorded beat-tone signal in the range from 10 Hz to 1 MHz. The integrated rms timing jitter obtained under optical injection represents a reduction of over 57% in comparison to the 150 fs measured from the laser in free-running conditions at 400 mA [9]. These results show that the injection of optical pulses, whose spectrum is centered over 20 nm away from that of the QDash MLLD, effectively changes the operation of the laser, synchronizing the free-spectral range of the laser to the ∼40 GHz spectral component of the injected signal and reducing the integrated timing jitter of the associated pulses. It is worth mentioning that, along with the operating conditions of the QDash laser (biased at 100 mA and temperature controlled at 25 °C), synchronization is sustained provided the following conditions of the injected pulses are met: a) Injected powers between þ6 and þ10 dBm, as measured by the variable optical attenuator (VOA) at port 1 of the optical circulator; b) A linear state of polarization [set by polarization controller (PC)] in close alignment to the transverse-electric eigen axis of the QDash laser waveguide; c) For the analyzed injection conditions, a frequency mismatch of approximately 5 MHz between the FSR of the laser in free-running and the fourth harmonic component of the injected pulses repetition rate.

The right-hand side of the optical spectrum (longer wavelengths) is shown in Fig. 3(b) for free-running and active mode-locking conditions of the QDash laser. Such spectra have been measured at the output of the laser and optical filter OBPF-3 (set at a bandpass width of 15 nm), respectively. Only selected modes from ∼1525 to ∼1531 nm are presented due to the limitations imposed both by the 20 MHz OSA and the optical amplification stage of the self-heterodyne setup. Indeed, the minimum measurable wavelength in the OSA utilized is around 1526 nm. In addition, the linear gain of the optical ampli-fier utilized at the input of the SHD setup is not sufficient for wavelengths below ∼1525 nm. It restricts the mea-surement of the filtered-modes, which after OBPF-3 present a significantly lower optical power. As illustrated in Fig. 3(b), all longitudinal-modes are shifted to longer wavelengths by ∼9 GHz. Sidebands at ∼10 and ∼20 GHz around each shifted longitudinal-mode appear due to the fundamental frequency and second harmonic components of the injected pulses. In addition, Fig. 3(c) shows the FWHM of the selected longitudinal-modes experiences a change in comparison to the free-running operation. In contrast to the behavior exhibited by this laser in free-running, where a quasi-linear profile of the optical linewidth is observed for all longitudinal-modes with their corresponding wavelength [9], a quadratic profile of the optical linewidth is obtained under optical synchronization. Starting with a linewidth of 3 MHz for the optical mode at 1531:01 nm, a minimum of 1:7 MHz is measured for the mode located at 1530:07 nm. From this minimum
linewidth, a quadratic increase is observed for shorter wavelengths within the analyzed range up to a maximum of 37:4 MHz for the mode at 1525:1 nm.

The trend of the optical linewidth with the wavelength indicates the synchronization process implemented in this experiment allows not only a reduction of the beat-tones linewidth and timing jitter, but also an improvement in the linewidth of some longitudinal modes in respect to the values measured at free-running conditions. The mechanism for this effect is the subject of further study. Notice that, although the modes around 1531 nm display a comparative linewidth for both free-running and injection-locking conditions at 100 mA, the electrical signal at the output of the SHD setup does not solely feature a Lorentzian shape for the modes in passive mode-locking, but also small sidebands. When isolated, they are best fitted with a Lorentzian shape, too, and are located around 5 MHz from the main component. Such a combined signal is shown in the inset of Fig. 3(c) and might indicate an incomplete passive mode-locking mechanism. In this sense, data in Fig. 3(c) showing the optical linewidth in free-running conditions at 100 mA have been obtained considering only the main Lorentzian component, but displayed values are increased by ∼50% if the envelope of the combined signal is taken into account.

It is worth noticing the beat-tone linewidth and timing jitter reduction obtained after external synchronization are achievable for bias currents in the range from ∼90 to 120 mA. It has been observed that the same range allows the synchronization of the QDash laser to optically injected pulse sequences at 10 GHz (and also at 20, 40, 80 and 160 GHz), as well as non-return-to-zero data streams at 40 Gbps for clock-recovery functionalities, as reported in [11,12], respectively. In this context, the current around 100 mA provides both a biasing condition for external synchronization operation and a threshold to the passive mode-locking regime in the laser under investigation. As a matter of fact, well-defined pulses featuring a width of ∼6 ps start to appear from a bias current of 100 mA while the QDash MLLD is in passive locking conditions [3].

To conclude, we have demonstrated the performance of a DC-biased QDash MLLD as an optical 40 GHz signal generator is improved by its synchronization to the fourth harmonic of a 10 GHz optical pulse stream even though both optical signals are detuned by 20 nm. The optical 40 GHz signal from the synchronized MLLD exhibits a linewidth of 8 Hz at most and an integrated timing jitter of 64 fs. Moreover, a minimal value of 1:7 MHz in the optical linewidth is obtained.

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Figures

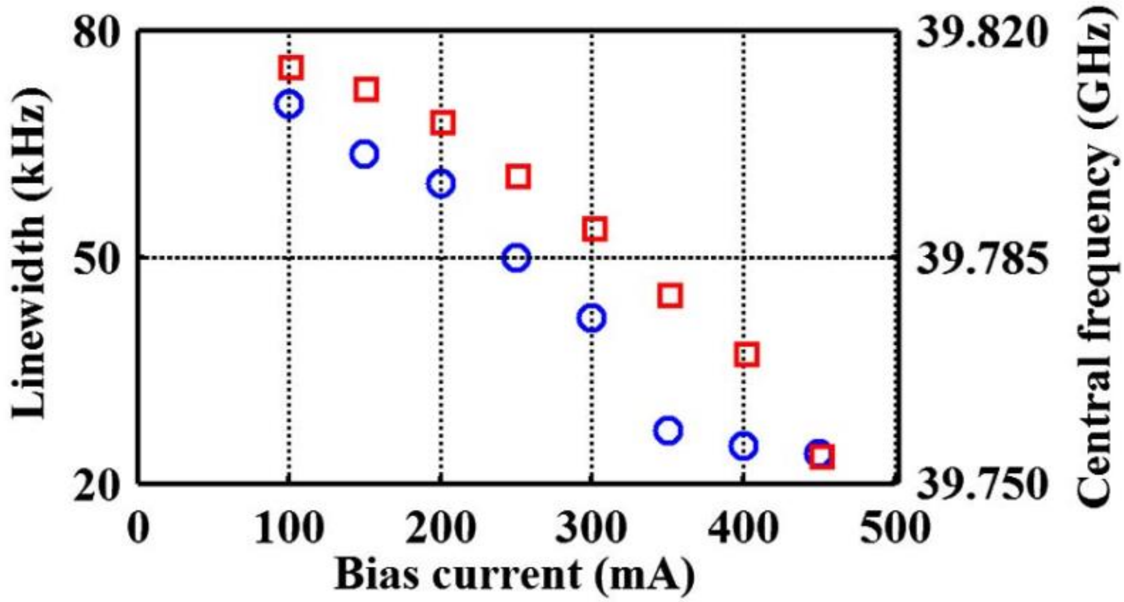

Fig. 1. (Color online) Linewidth (∘) and central frequency (□) of the beat-tones at the output of the QDash MLLD in passive mode-locking operation for bias currents from 100 to 450 mA.

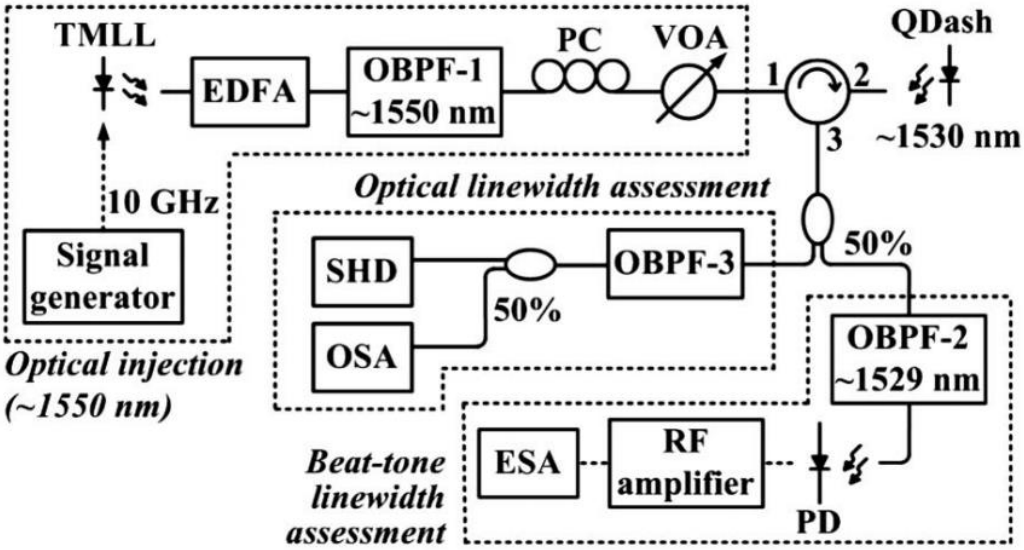

Fig. 2. Experimental setup for assessing the optical and mode-beating linewidths of the QDash MLLD operating under optical injection.

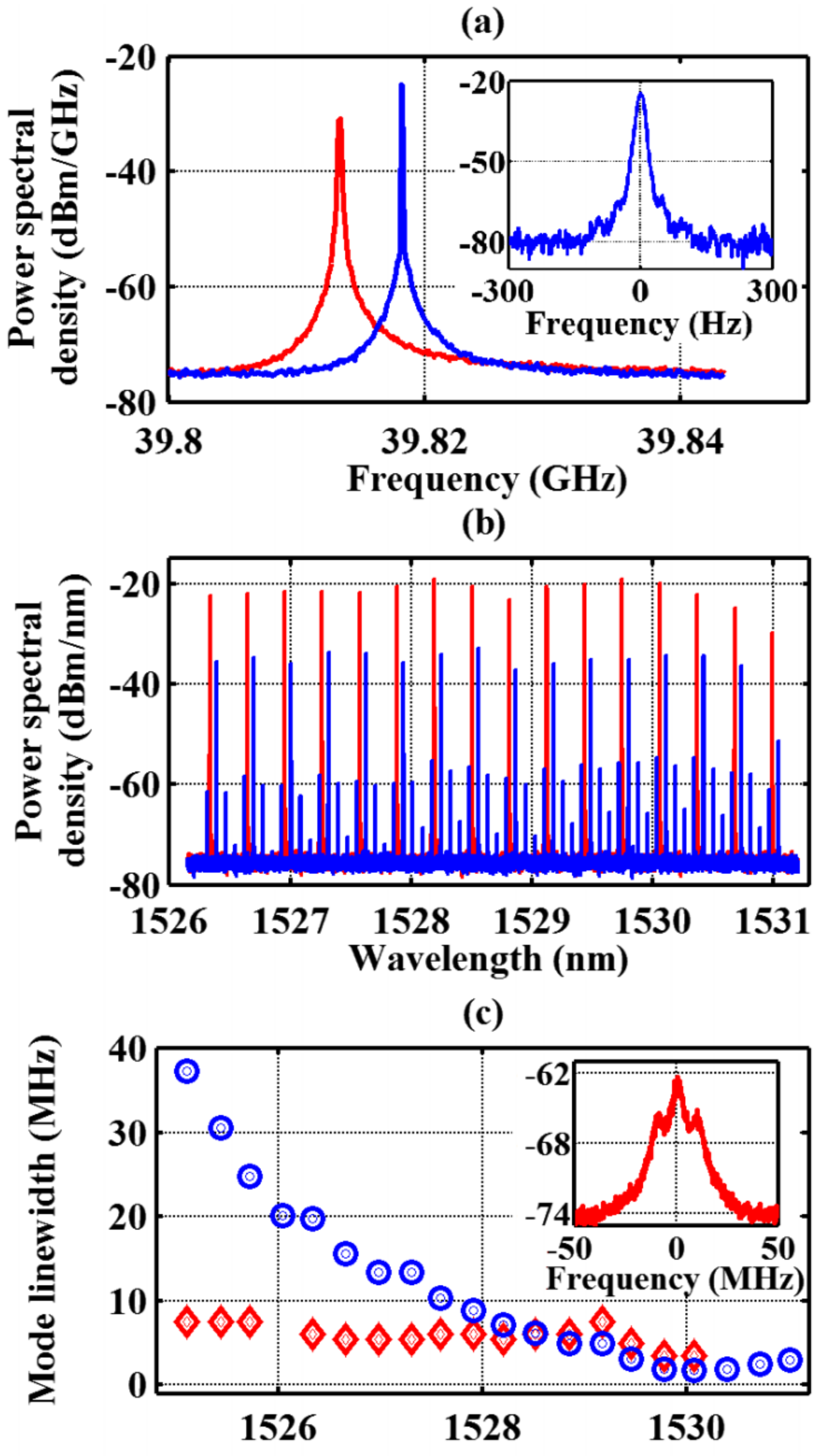
(a)
Power spectral density (dBm/GHz)
-20
-40
-60
-80
39.8
39.82
39.84
Frequency (GHz)
-20
-50
-80
-300
0
300
Frequency (Hz)
(b)
Power spectral density (dBm/nm)
-20
-40
-60
-80
1526
1527
1528
1529
1530
1531
Wavelength (nm)
(c)
Mode linewidth (MHz)
40
30
20
10
0
1526
1528
1530
Wavelength (nm)
-62
-68
-74
-50
0
50
Frequency (MHz)

Fig. 3. (Color online) (a) Beat-tones, (b) optical spectrum and (c) linewidth of selected modes for the QDash MLLD in free-running (red trace) and under the injection of optical pulses (blue trace). Bias current in the QDash laser is set at 100 mA. Insets in (a) and (c) illustrate the beat-tones under optical injection recorded with a 10 Hz resolution and the signal at the output of the SHD while the laser is in free-running, respectively.

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