Timing-jitter, optical, and mode-beating linewidths analysis on subpicosecond optical pulses generated by a quantum-dash passively mode-locked semiconductor laser

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Abstract Timing-jitter measurements in optically generated subpicosecond pulses by a quantum-dash passively mode-locked semiconductor laser as a function of the bias current are reported. All the measurements are retrieved from a second-harmonic-generation frequency-resolved optical gating system. A decreasing trend in the pulse width and the associated timing jitter is found with the bias current. Additionally, the optical and mode-beating linewidths are analyzed in terms of both the mode wavelength and the bias current. From our results, we can conclude that once the optical modes are phase-locked, the optical linewidth associated to every individual longitudinal mode of the device under test does not have a significant impact on the mode-beating signal on neither the pulse width nor its respective timing jitter.

Quantum-dash mode-locked (QDash-ML) laser diodes (LDs) have attracted significant interest in optical time-domain multiplexing systems as an effective approach for all-optical short-pulse generation and all-optical clock recovery. Short-pulse generation from 40 GHz [1] to 346 GHz [2], as well as frequency multiplication at 270 GHz [3] by passive mode-locking in single-section QDash-MLLDs, have been reported. All-optical clock-recovery at 40 Gbps [4,5] has been demonstrated by active mode locking in single-section quantum-dot epitaxies. Apart from the low power consumption and compact size, the fast carrier dynamics as well as the broad and nearly flat gain spectrum in both 1300 nm and 1550 nm are among the more attractive features of QDash/QDot ML lasers. Another important feature in such devices is the very narrow mode-beating linewidth [6,7], leading to either a small timing jitter in short-pulse generation or a reduction of timing jitter up to 200 fs in all-optical clock-recovery applications [4,5]. In spite of such remarkable achievements, to the best of the authors' knowledge, an analysis of the timing jitter associated with the optically generated pulses has not been reported under passive mode-locking conditions. Indeed, the assessment of such timing jitter has significant importance when using the QDash-MLLD as a short-pulse generator at high repetition rate. The aim of this Letter is twofold: (i) to perform a detailed experimental analysis of the linewidths as-sociated with both the optical modes and the 40 GHz mode beating and (ii) to measure the timing jitter as-sociated with the generated pulses from a single-section QDash-MLLD. After our experiment, a decreasing trend in the optical linewidths as the wavelength increases is found at a given bias. Furthermore, a decreasing trend in the timing jitter with bias current is observed, while the mode-beating signal presents a fairly constant linewidth. It can be concluded that in our laser under test all the optical modes are strongly passively mode-locked as opposed to previous analysis performed on similar laser structures, where a different strength of the passive mode-locking mechanism has been observed after using a filtering scheme at the laser output [6].

Our device under test (DUT) is a 1-mm-long single-section, without phase or saturable absorber section, dc-biased, multimode QDash Fabry-Pérot (FP) semiconductor LD [1]. A brief description of the QDash-based heterostructure, as well as features and dimensions of the active core in order to achieve emission at 1.55 μm have been given in [1]. From a typical collected optical power versus bias current (LI curve) characterization, it is found the laser under test presents a bias threshold of 18 mA and a total collected power of 4 mW when operating at 400 mA and temperature controlled at 25° C. The collected light is recorded on a slow-response optical power meter as a function of the increasing and decreasing bias current. Based on this characterization, no hysteresis behavior is observed, confirming the standard LI dependence of a single-section FP laser.

The experimental setup utilized to characterize the linewidths and timing jitter is depicted in Fig.1. Regarding the linewidth assessment, the laser output is first coupled to an isolator (ISO) for suppressing back reflections and then to a tunable optical band-pass filter (BPF), allowing every individual optical mode (optical linewidth measurement) and pair of consecutive modes (mode-beating measurement) to be selected and analyzed. In the case of the mode-beating linewidth measurements, a 50 GHz photodetector (PD) and an electrical spectrum analyzer (ESA) set at 1 MHz span and 1 kHz video bandwidth is utilized, while for the optical linewidth measurements a self-heterodyne detection (SHD) setup is implemented prior to the PD and ESA. A semiconductor optical amplifier (SOA) operating in linear regime is used to boost the optical modes after the BPF, al-lowing sufficient optical power to be provided to the SHD. In addition, the timing jitter associated with the optical pulses generated by our DUT is analyzed with a second-harmonic-generation (SHG) frequency-resolved optical gating (FROG) system, with temporal and wavelength resolutions of 26 fs and 0.02 nm, respectively. Thus the experiment is performed by measuring the linewidths (optical and mode beating), and the timing jitter of the optically generated pulses by setting the dc-bias current from 150 mA to 450 mA. The timing jitter analysis is performed on the pulses generated by our DUT after a passive compression scheme, achieved with a 450-m-long single-mode fiber (SMF) [1]. Indeed, when fitted to a Gaussian shape, the pulses exhibit a minimum FWHM of 2.2 ps and 720 fs at the laser output and after the passive compression scheme, respectively (see inset on Fig. 2(a), the pulse profile at the MLLD output is shown in the dotted curve and after compression in the solid curve). The linewidth measurements are performed with and without the addition of such an SMF, confirming they are not affected by our compression scheme.

A typical optical spectrum collected at the DUT output is shown in Fig. 2(a). At 350 mA, it exhibits more than 30 longitudinal modes with 0.31 nm inter-modal separation, giving an optical FWHM band-width of 12 nm centered at 1526 nm. After tuning the BPF from the shortest 1520 nm to the longest wavelength 1532 nm falling into the 3 dB bandwidth of the laser spectrum, the optical linewidth as-sociated to each longitudinal mode as a function of the bias current is measured and depicted in Fig. 2(b). In this case, the BPF is set to 0.2 nm bandwidth, allowing the filtering of each longitudinal mode with a minimum adjacent-mode suppression of 25 dB. Moreover, the FWHM linewidth is obtained by a Lorentzian fitting of each optical mode resolved. As it is shown in Fig. 2(b), a decreasing trend in the optical linewidth is observed as a function of the mode wave-length at a given bias current. Furthermore, a change in the magnitude of the mode linewidth is observed as a function of the bias current. For instance, it changes from 45 MHz to 10 MHz at a bias of 350 mA, while a minimum mode linewidth ranging from 20 MHz to 5 MHz is achieved at 250 mA (limited to a resolution of 17 kHz set by the used SHD setup).

In the rf domain, a Lorentzian line shape corresponding to the mode-beating signal is measured from our DUT as a photocurrent on the fast PD and depicted in Fig. 3(a) for a bias current of 350 mA. After tuning the BPF within the same range as that of the optical mode linewidth measurement, a fairly constant profile of the mode-beating FWHM line-width is observed. Indeed, it fluctuates from 10 kHz to 25 kHz regardless of the bias supplied, as shown in Fig. 3(b). To retrieve these data, the filter is tuned so that a pair of adjacent optical modes passes through it, allowing a proper detection of the mode-beating signal on the PD. In addition, the mode-beating linewidth is obtained by a Lorentzian fitting of the photocurrent measurements. A maximum line-width of 25 kHz is measured when the entire optical spectrum (without the BPF) is considered. The behavior of the sharp mode-beating linewidth with re-spect to the mode wavelength implies that all the longitudinal modes are strongly mode-locked, regardless of the mode position on the optical spectrum and the dc-bias current supplied to the device.

Finally, the width of the optical pulses generated by the passively MLLD under test, as well as the as-sociated timing jitter (both of them retrieved from the FROG system), are shown in Fig. 4

as a function of the bias current. In the case of the timing jitter τ_j, it is calculated by considering the intensity auto- and cross-correlation traces according to the relation $\tau_J = \frac{\tau_P}{\tau_{ac}}\sqrt{\tau_{cc}^2 - \tau_{ac}^2}$ where τ_{ac} and τ_{cc} are the FWHM of the auto- and cross-correlation pulses, respectively.

The time-domain approach implemented for measuring the timing jitter is quantitatively comparable to the frequency-domain technique. Its advantage is that it requires neither an extremely fast photodetector nor a so-called timing jitter analyzer. As can be observed in Fig. 4, the pulse width tp and associated tj present a decreasing trend with the dc bias. For instance, tj associated with the widest measured pulse (tp = 1.6 ps, obtained at 150 mA) is above 350 fs, while τ_J associated to the shortest pulse (tp = 720 fs, obtained in the range from 300 to 450 mA) is 150 fs. This might imply that optical modes have altogether a better quality of their respective phase-locking mechanism at dc-bias conditions ranging from 300 to 450 mA than the phase locking obtained at a lower bias current.

Notice that even though the 25 kHz mode-beating linewidth of the DUT is inferior with respect to the narrowest linewidth obtained from a 4-mm-long two-section passively mode-locked QD de-vice at 10 GHz [7], its performance is comparable in terms of the timing jitter (minimum of 150 fs with respect to 147 fs reported in [7]). Moreover, considering a collected power of 4 mW at our DUT output with τ_p = 2.2 ps at 40 GHz, a peak power of 40 mW is estimated, while for compressed pulses of 720 fs the peak power is 140 mW. Such measurements are comparable with previous work, where a peak power of 2.25 W has been estimated from a 2.4-mm-long two-section mode-locking tapered QD device whose out-put power is 15.6 mW and 360 fs pulses are generated at 17 GHz [8].

In summary, a detailed experimental analysis of the linewidths and the timing jitter associated with the short pulses generated from a QDash-MLLD has been achieved. Once the optical modes altogether are mode-locked, the optical linewidth associated to every individual longitudinal mode of the DUT does not have a significant impact on the mode-beating signal neither on the pulse width nor on its respective timing jitter. In addition, the performance of the analyzed device as an all-optical short pulse generator is comparable with some other MLLDs reported in the literature in terms of pulse width, timing jitter, and output power.

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Figures

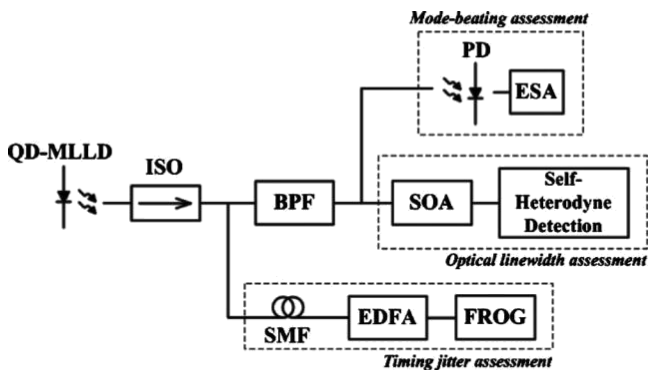

Figure 1Schematic of the experimental setup. Abbreviations are defined in the text.

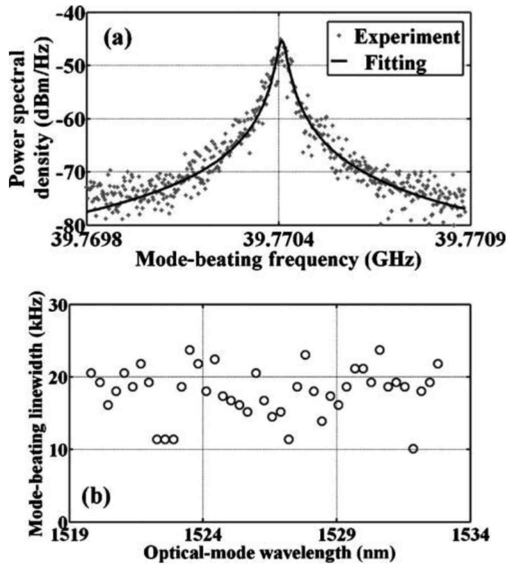

Figure 2(a) Typical optical spectrum collected from the QDash-MLLD at 350 mA and (b) mode linewidth measurements as a function of the bias current. In the inset, pulse profile at the output of the QDash-MLLD (dotted curve) and after passive compression (solid curve).

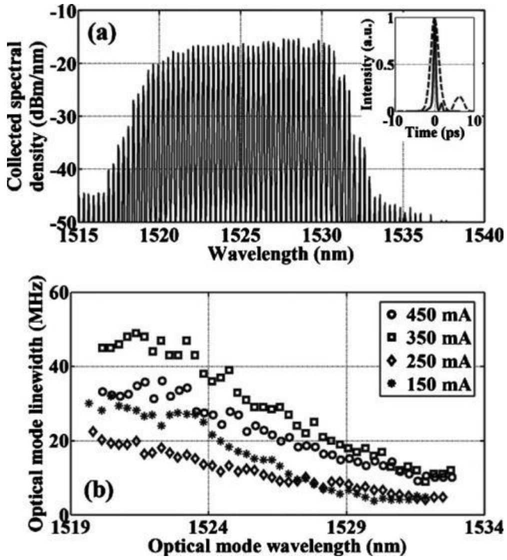

Figure 3 (a)Typical mode-beating signal measured at the output of our QDash-MLLD at 350 mA and (b) mode-beating linewidth associated with each pair of optical modes as a function of the BPF central wavelength.

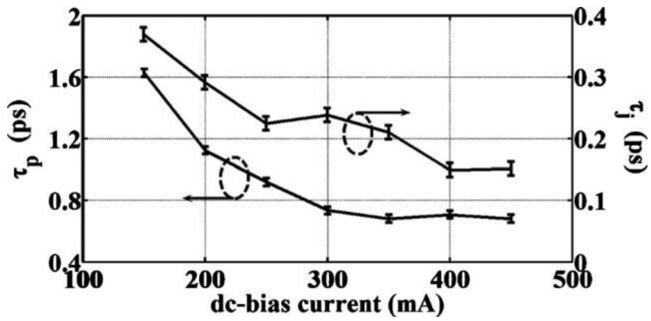

Figure 4 Pulse width tp and timing jitter tj associated with the optically generated pulses in terms of the dc-bias current supplied to the DUT.