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Sub-kHz RF linewidth of quantum-dash mode-locked laser by self-injection from symmetric dual-loop feedback and fiber delay

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Abstract: Sub-kHz RF-linewidth was demonstrated in two-section quantum-dash mode-locked lasers emitting near 1550 nm and 20 GHz repetition-rate using symmetric dual-loop and fiber delay. Compared to free-running lasing, RF-linewidth and timing-jitter reduced by ~100x and ~10x.
OCIS codes: (140.4050) Mode-locked Lasers; (250.5590) Quantum-well, -wire and -dot devices.

1. Introduction

Generation of low-jitter optical pulses in semiconductor mode-locked lasers (MLLs) is of particular interest for stable pulse source, all-optical clock recovery, Lidar, optical frequency combs, nonlinear integrated optics, and microwave applications [1]. Quantum-dot/dash MLL are attractive because of fast carrier dynamics and broad gain spectra provided by these novel materials [2]. Compared to quantum well and bulk lasers, quantum-dot/dash lasers have superior properties such as low transparency current density, high thermal stability, low amplitude and phase noise, which makes them attractive candidates as robust low noise MLL[3, 4].

Linewidth and timing jitter of beat-tones are two key properties of the optical pulse trains. Both can be reduced by optical feedback [5] or external modulation [6]. Here, we demonstrate reduction of RF linewidth and timing jitter of optical pulse trains from quantum-dash (QDash) MLL by self-injection with symmetric dual-loop feedback and a long fiber spool.

2. Experimental results

The experimental scheme is shown in Fig. 1 (a). Our experiment used a two-section Fabry-Perot laser chip with InAs/InP quantum-dash active layers (Dash in a Well structure), which operated at the most important optical communication window ~1.55 μm [2]. One section was biased above transparency to provide gain, the other kept open as reverse biased for saturable absorption. The gain section was driven at 300 mA (lasing threshold is ~130 mA), the saturable absorber section was kept open. Heat sink temperature was 292 K. A SOA was used to amplify the pulses with gain 9.8 dB. We employed symmetric dual-loop feedback together with a single-mode fiber spool (~ 250 m) to reduce the RF linewidth and timing jitter. In either loop, pulses have the same power and phase shift, which was realized by using variable attenuators and optical delays. The length of each feedback loop without the fiber spool was ~ 6 m. Optical coupling of QDash MLL chip was realized using tapered fibers. The optical spectrum of the free-running QDash MLL is shown in Fig. 1 (b). The spectral width is ~ 10.5 nm at -3 dB, covering 62 modes. RF measurements of the pulses were carried out using a 33 GHz bandwidth photodiode coupled to a RF amplifier (~18 dB) then an ESA. The RF spectrum of free-running QDash MLL on ESA and its Lorentzian fit are shown in Fig. 1 (c). Its RF linewidth and integrated root mean square (RMS) timing jitter are 97.9 kHz and 4.27 ps, respectively.

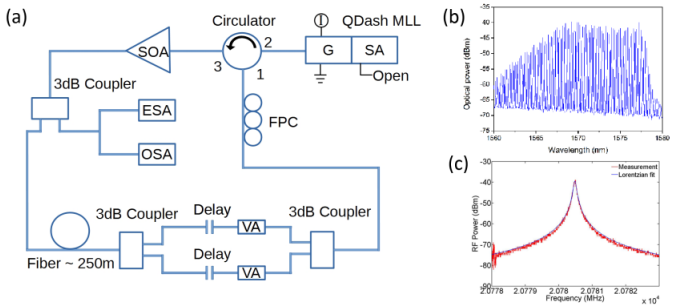


Fig. 1. (a) Experiment setup. G: gain section, SA: saturable absorber, SOA: semiconductor optical amplifier, ESA: electronic spectrum analyzer, OSA: optical spectrum analyzer, FPC: fiber polarization controller, and VA: variable attenuator; (b) optical spectrum of free-running QDash MLL; (c) RF spectrum of free-running QDash MLL and its Lorentzian fit.

The power ratio between the feedback from either loop and the QDash MLL was fixed at -23 dB. The total feedback power ratio is -20 dB. RF spectra with different fiber lengths are shown in Fig. 2 (a). Compared to the RF linewidth of the free-running QDash MLL in Fig. 1 (c), RF linewidths with symmetric dual- loop feedback are much narrower. The QDash MLL with dual-loop feedback can be regarded as the superposition of two single feedback loops, and the two fiber paths inserted between 3dB couplers form a Mach-Zehnder (M-Z) fiber interferometer. The path difference of this interferometer is finely tuned using variable optical delays. When modes in the outer and inner loops were aligned, constructive interference stabilized the optical pulses in the M-Z fiber interferometer. The constructive interferometer made the RF peak and supermodes narrower and sharper as shown in Fig. 2 (b), which resulted in stabilization of pulses [7]. In addition, the RF linewidth is proportional to 1/loop length, as shown in the inset: the RF linewidth is reduced as the loop length increases since more of the optical energy is stored in the system. Thus, the narrowest RF linewidth of 972 Hz was acquired using dual-loop feedback and a 250 m long fiber spool, whereas the widest RF linewidth of (32.7 kHz) was without the spool (0 m). Supermode noise in evident in the RF spectra in Fig. 2 (c). The central frequency of the supermodes shifts away from the peak with increasing fiber length. The SSB phase noise spectra with dual-loop feedback and different fiber lengths are shown in Fig. 2 (d). The SSB phase noise reduces from -74 dBc/Hz to -87 dBc/Hz at 100 kHz frequency offset with increasing fiber length. The integrated RMS timing jitter was calculated using the equation in Ref. [7], and shows an approximate dependency on root square of RF linewidth. So as shown in the inset, the square of integrated RMS timing jitter is approximately proportional to 1/loop length. A minimum integrated RMS timing jitter of 430 fs was acquired using dual-loop feedback and a 250 m fiber spool. In addition, the timing jitter could be reduced further by omitting the SOA and the excess noise if introduced.

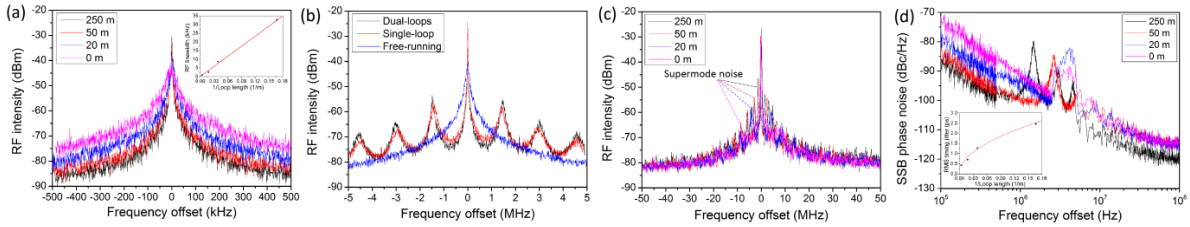


Fig. 2. (a) RF spectra with different fiber lengths, span is 1MHz, the inset is RF linewidth as a function of 1/loop length (including additional loop length of ~6 m); (b) RF spectra with single-loop feedback, dual-loop feedback, and without feedback, the inset is the corresponding optical spectra. (c) RF spectra with different fiber lengths, span is 100 MHz; (d) SSB phase noises spectra with different fiber lengths, the inset is integrated RMS timing jitter as a function of 1/loop length.

3. Conclusion

We have demonstrated RF linewidth narrowing and improved stabilization of optical pulses from QDash MLLs with symmetric dual-loop feedback and fixed 250 m fiber delay. The RF linewidth and integrated RMS timing jitter were dramatically reduced from 97.9 kHz and 4.27 ps when free-running to 972 Hz and 430 fs In addition, the SSB phase noise was reduced from -74 dBc/Hz to -87 dBc/Hz at100 kHz frequency offset. Thus, the scheme of self-injection based on symmetric dual-loop feedback enables the reduction of the RF linewidth, timing jitter and phase noise without need of microwave or optical filtering.

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