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Youcef Driouche, Badr-Eddine Benkelfat, Kamel Merghem. Ultra-narrow linewidth and long-term stabilized self-injected Qdash semiconductor comb laser for ultrafast optical ranging systems. Optica Laser Congress and Exhibition, Optica and American Physical Society's Division of Laser Science (DLS), Oct 2024, Osaka (Japan), Japan. hal-04675595

HAL Id: hal-04675595

<https://hal.science/hal-04675595>

Submitted on 22 Aug 2024

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Ultra-Narrow Linewidth and Long-Term Stabilized Self-Injected Qdash Semiconductor Comb Laser for Ultrafast Optical Ranging Systems

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Abstract: We demonstrate the significant impact of resonant feedback on the long-term stability, phase noise, and optical linewidth of a single-packaged quantum-dash comb laser using a hybrid feedback architecture, aiming to enhance performance for LiDAR systems. © 2024 The Author(s).

1. Introduction

The advent of Quantum-Dash Mode-Locked Laser (QD-MLL) has opened new horizons for high-precision optical ranging and LiDAR systems, offering a compact, easy-to-operate, and highly efficient solution for modern optical technologies. These lasers are particularly advantageous due to their integration capabilities, enabling robust and low-cost photonic devices suitable for autonomous navigation, industrial sensing, and 3D digitization [1-2]. Their ability to produce high measurement rates and substantial optical output power sets them apart from traditional comb sources, ensuring superior performance and scalability.

Our research demonstrates how the impact of resonant self-injection, using a hybrid architecture, significantly enhances long-term stability of a single-package QD-MLL by reducing frequency drift excursions from 140 kHz to 50 kHz. Additionally, it improves the RF linewidth of the comb modes down to 600 Hz at -3 dB, and reduces the optical linewidth to less than 500 kHz at -3 dB for all modes. This research sets a new benchmark for future developments in photonic integrated circuits for LiDAR systems.

2. Experimental setup and results

The experimental setup is described in Fig. 1. The investigated device is based on Quantum dash nanostructures active layer with a cavity length of 1712 μm , corresponding to a repetition frequency of about 24.94 GHz. The chip on submount was assembled to a polarization-maintaining (PM) fiber at 1550 nm wavelength, and integrated into a butterfly package equipped with a Peltier element for temperature control. The injected current was fixed to 250 mA, corresponding to 10 times the threshold current (25 mA), offering a nearly flat comb of 14.65 nm bandwidth at -10 dB, with 70 modes centered at 1540 nm, and maintained at a temperature of 25°C. A portion of light was sent to an optical bench (FB-76, Thorlabs) through a 75/25 coupler. The bench contains a fiber-port collimator (PAF2A-A10C, Thorlabs), two polarizers (FBRP, Thorlabs), and a free-space gold mirror mounted on single-axis flexure translation stages (NF15AP25, Thorlabs). We should mention that the reason for using two polarizers is twofold: the first polarizer was used to maximize the feedback effect by matching the feedback and the emitted TE light polarizations, as the entire fiber is PM, and the second polarizer controls the feedback strength. Also, the translation stage of the mirror was controlled via a piezo controller to target the resonant feedback regime. This hybrid architecture (fiber/free-space) ensures a stable environment, as every element is fixed and no mechanical disturbances will occur during the experiment. On the other hand, the feedback signal was combined with a tunable external cavity laser (ECL) using a 75/25 coupler to measure the optical linewidth of the comb by using the conventional heterodyne technique. The collected light is sent to an optical spectrum analyzer (OSA, Anritsu MS9740B), and a 25 GHz bandwidth amplified photodiode coupled with an electrical spectrum analyzer (ESA, R&S FSVR).

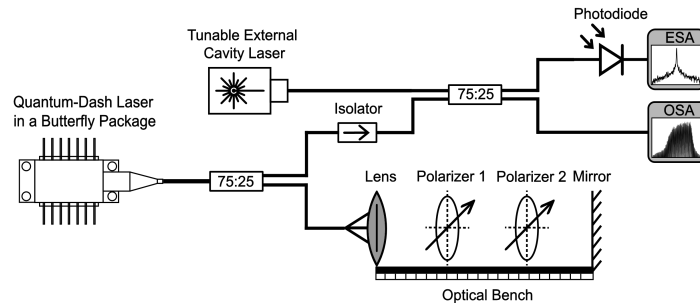


Fig. 1. Experimental setup. ESA: Electrical Spectrum Analyzer, OSA: Optical Spectrum Analyzer.

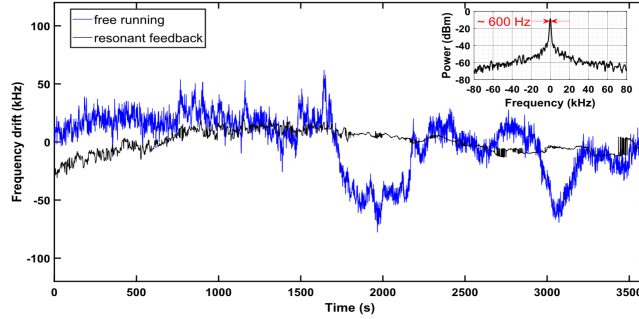


Fig. 2. Frequency drifts during 1h, free running vs. resonant feedback. Inset: RF spectrum with resonant feedback ($\Delta v_{\text{RF-resonant feedback}} = 600 \text{ Hz}$ at -3 dB).

Fig. 2 depicts the frequency drifts for the free-running and resonant feedback configurations. The measurement was performed with a 1s gate time over 1h. Without feedback, the RF frequency shows an excursion of 140 kHz which is partly caused by an external noises (current source, temperature fluctuations...). In comparison, applying resonant feedback reduces the frequency drift excursion to 50 kHz and eliminates the large fluctuations present in long-term operation. During the experiment, the RF linewidth in the free-running case was found to be $\Delta v_{\text{RF-free-running}} = 14.3 \text{ kHz}$ at -3 dB. In contrast, resonant feedback forced the RF frequency to shift by $\sim 3 \text{ MHz}$ towards high frequencies, and the RF linewidth to be very narrow, as shown in the inset of Fig. 2. Using a span of 200 kHz, a resolution bandwidth of 1 kHz, and a video bandwidth of 1 kHz, the RF linewidth was found to be $\Delta v_{\text{RF-resonant feedback}} = 600 \text{ Hz}$ at -3 dB. This linewidth reduction is expected to decrease the timing jitter by a factor of ~ 5 [3].

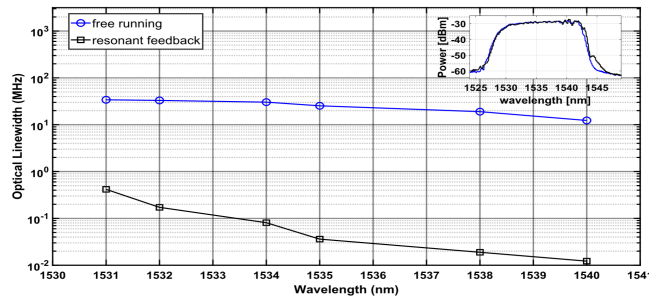


Fig. 3. Optical linewidth as a function of wavelength. Inset: Optical spectrum measurement.

Fig. 3 shows the individual optical comb linewidth measurements with and without feedback. The measurements were performed by scanning the ECL over the entire bandwidth of the comb lines from 1531 nm to 1540 nm. The linewidths without feedback are considerably higher, ranging from 34.06 MHz to 12.33 MHz at -3 dB. When resonant feedback is implemented, there is a substantial reduction in linewidths, with values dropping to between 417 kHz and 12.2 kHz at -3 dB. This dramatic decrease in linewidth highlights the effectiveness of resonant feedback in stabilizing the optical comb. Notably, the optical linewidth is reduced by a factor of up to 10^3 . Alternatively, as shown by the OSA in the inset of Fig. 3, the comb envelope appears shifted for a few nm to longer wavelengths in the presence of feedback compared to the free-running envelope, while maintaining its shape.

Conclusion

Our study demonstrates the significant improvements of QD-MLL achieved by applying resonant feedback to a single-packaged quantum-dash laser using a hybrid feedback architecture. The key findings highlight the enhanced performance in terms of long-term stability, phase noise reduction, and optical linewidth narrowing, which are paramount of importance for ultrafast LiDAR systems.

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