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# Quantum-Dash Mode-Locked Laser Behavior Under External Optical Feedback Strength

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**Abstract:** We experimentally identified different optical coherent feedback sub-regimes of a quantum-dash mode-locked laser as a function of the feedback strength. The results render the laser a versatile source. © 2023 The Author(s).

## 1. Introduction

The quantum-dash mode-locked laser (QD-MLL) stands as an innovative device in the realm of optoelectronics, promoting the field of ultrafast lasers into new frontiers. This type of laser offers large flat and equidistant optical frequency combs spaced by tens of GHz and unrivaled capabilities with its unique chip-scale design, low production costs, and simple operation by a DC current. Among the various comb generator concepts, the QD-MLL shows promise as a competitive device for high-speed data transmission with advanced modulation formats as well as local oscillators for parallel coherent reception [1,2].

Optical feedback with an external cavity has been used as a solid method to narrow the RF linewidth of the QD-MLL individual modes, thus reducing the phase noise. Most of the reported studies have focused on adjusting the external cavity length to target the coherent feedback regime such that the external cavity length is close to an integer multiple of the QD-MLL cavity.

In this paper, we experimentally identified different coherent feedback sub-regimes of QD-MLL based on the feedback strength while the external cavity length is fixed. Under specific circumstances, we show that the linewidth of the RF beat note could be tuned as a function of the feedback strength, and the optical envelope could be shifted for a few nm.

## 2. Principle of operation and experimental results

Fig. 1 sketches the experimental setup implemented. The device under test has a 22.61 GHz free spectral range at 100 mA DC current, corresponding to 4 times the threshold current (25 mA), a nearly flat envelope of 9.5 nm bandwidth at -10 dB centered at 1556 nm, and as-cleaved mirror facets. To avoid temperature drift, the laser was set on a heatsink and stabilized at  $\approx 25$  °C using a Peltier cooler. The light emitted from the first facet of the QD-MLL is coupled to a lensed fiber equipped with an anti-reflection coating for 1550 nm to reduce optical back-reflection into the laser cavity. The coupled light is sent via a 50/50 coupler to a fast amplified photodiode (PD, RXM25AA, 25 GHz bandwidth), coupled with an electrical spectrum analyzer (ESA, R&S FSVR, 30 GHz bandwidth) for extracting the RF beat note at the FSR frequency with 10 kHz resolution bandwidth and 800 kHz span, and an optical spectrum analyzer (OSA, Anritsu MS9740B) with 1 nm resolution bandwidth and 15 nm span. On the second facet of the laser, the feedback loop contains a collimating lens, a polarizer acting as a variable attenuator to control the feedback strength, and a free-space gold mirror. The feedback strength is known as the ratio of the intensity reflected back into the laser cavity after one round-trip in the free-space cavity to the intensity emitted from the laser. The mirror position is fixed such that the external cavity length becomes a multiple of the laser cavity length to target locking between the two cavities.

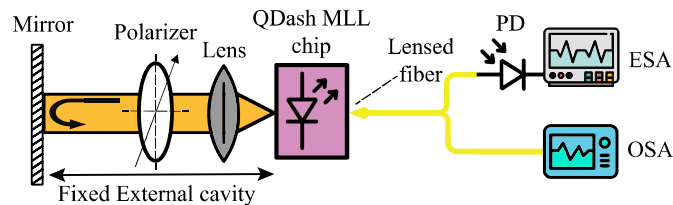


Fig. 1. Experimental setup. QDash MLL: Quantum-Dash Mode-Locked Laser, PD: Photodiode, ESA: Electrical Spectrum Analyzer, OSA: Optical Spectrum Analyzer.

Different coherent feedback sub-regimes are identified by rotating the polarizer at different angles, starting with the maximum feedback strength. Fig. 2 (a) shows the RF beat note as a function of different polarizer angles. When the polarizer is parallel to the polarization state of the light emitted from the laser ( $\theta = 80^\circ$ ), strong feedback is applied, calculated to be around -7 dB, and the optical modes widen to the point where almost nothing is observed in the RF domain. This regime corresponds to the coherence collapse regime as reported in [3] with regard to quantum-dot lasers. With a feedback strength close to -16 dB ( $\theta = 110^\circ$ ), which is the boundary level between the coherence collapse regime and the first appearance of a narrow RF beat note observed with a 6.5 kHz linewidth at -3 dB, corresponding to an efficient mode-locking regime. The power of the narrow RF beat note was found to be at least 10 dB greater than that of the free-running case. The RF beat note linewidth started to broaden by attenuating the feedback strength, taking 10, 11.7, 13.5, and 17 kHz at -3 dB when the polarizer angles were 120, 130, 140, and  $150^\circ$ , respectively. These results indicate a strong relationship between the feedback strength and the phase locking between the laser modes, and coherent feedback sub-regimes exist depending on the feedback strength and not only the length of the external cavity. These coherent sub-regimes appear if the feedback strength is between -27 and -14 dB. By going forward for angles  $165^\circ < \theta < 170^\circ$ , weak feedback is applied (lower than -27 dB), the RF beat note linewidth is almost ten times wider, and the RF peak power is 10 dB lower than the free-running case. Finally, we return to the initial state (free-running, 81 kHz RF beat note linewidth at -3 dB) when the polarizer is crossed with respect to the polarization state of the light emitted from the laser ( $\theta = 170^\circ$ ).

On the other hand, from the OSA in Fig. 2 (b), for the coherence collapse regime, the comb envelope appears modified and covers a wider bandwidth of 15 nm, and it is shifted to a longer wavelength compared to the free-running envelope. The comb envelope looks the same as in the free-running case for the other coherent sub-regimes but is shifted for a few nm to longer wavelengths. The polarizer effect leads to a reduction in the threshold carrier density and a decrease in photon emission energy, which may explain the redshift. The amount of the shift is highly dependent on the amount of energy being reinjected into the laser. The similarity in shape of the optical envelope with the free-running one could be related to a similar feedback phase affecting every individual comb mode. Finally, concerning the weak feedback, the optical envelope does not show any effect from feedback, unlike the RF beat note.

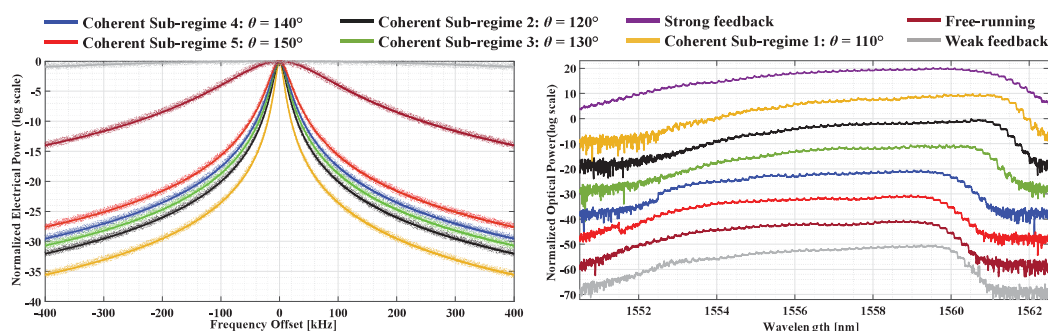


Fig. 2. Experimental results. (a) The different coherent sub-regimes obtained as a function of the feedback strength measured from the electrical spectrum analyzer (b) The corresponding comb envelope.

## Conclusion

In this work, we have shown experimentally that different optical coherent feedback sub-regimes appear depending on the feedback strength while the external cavity remains fixed. The versatility of these comb sources in terms of phase noise and spectral bandwidth could potentially meet the requirements of many applications, such as high-bandwidth coherent transmission and high-precision dual-comb optical ranging with chip-scale comb sources [4].

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