From chaotic lasers to sensing and computing applications :

Focus on Optical Feedback-Induced Quasiperiodic Cascade in Optically injected Semiconductor Lasers

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Optical injection (OI) is well established technique for stabilizing laser frequency and linewidth or for enhancing nonlinear dynamical behaviour [1]. When optical feedback (OF) is added to an optically injected (OI) laser, the injection-locking (IL) region is altered, typically shifting toward negative detunings and the system exhibits richer, more intricate unlocked dynamics [2,3]. Although asymptotic analyses predict that OF should induce an oscillatory IL boundary [4], this effect has not yet been experimentally confirmed. Our recent numerical studies reveal that optical feedback profoundly reshapes the transition to locking, giving rise to a cascade of quasiperiodic bifurcations [5]. As the drive frequency is varied, the response laser alternates between periodic, quasiperiodic, and chaotic states, with the feedback delay playing a decisive role in this sequence. Such hybrid OI–OF configurations hold strong potential for applications in random number generation and neuromorphic photonics, underscoring the need for a deeper understanding of their underlying dynamics.

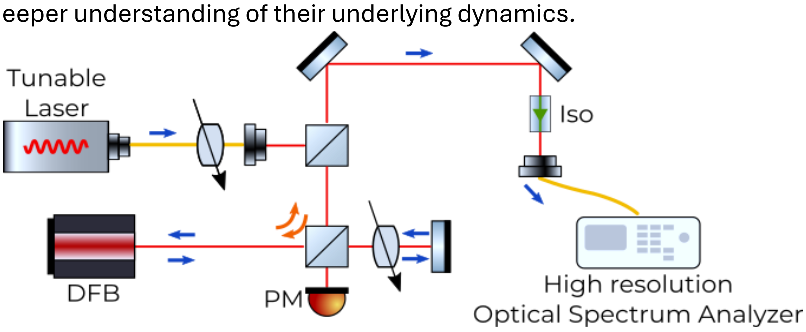

Fig 1 : Experimental free-space set-up of a laser diode under both OI and OF. PM: Power meter. ISO: optical isolator.

We experimentally investigated the nonlinear dynamics of a free-space laser diode operating at 1550 nm under simultaneous optical injection and optical feedback. The feedback delay was set to τ = 0.5 ns, corresponding to an external-cavity frequency of $f_{ec} = 1/\tau = 2\ GHz$. The experimental setup, shown in Fig. 1, uses a tunable master laser for injection, while both injection and feedback rates are independently controlled through variable optical attenuators. For the first time, we observe a periodic alternation between time-periodic and quasiperiodic regimes outside the injection-locking region, in excellent agreement with recent numerical predictions [5]. Remarkably, two distinct dynamical scenarios are identified, depending on whether the feedback operates in the short- or long-cavity regime, that is, depending on the feedback delay relative to the relaxation oscillation period.

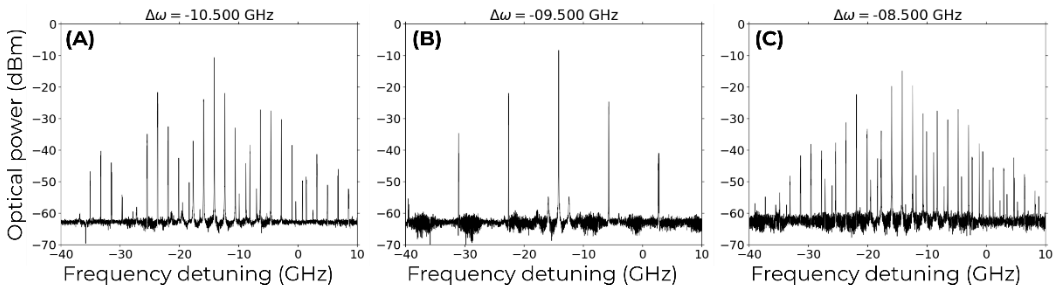

Fig 2 : Experimental optical spectra of the response laser for different detunings, $\kappa_{inj} = 1.1\%$, $\Delta\omega =$ (A) $-10.5\ GHz$, quasiperiodic regime induced by injection and f_{ec}; (B) -9.5 GHz, injection induced time-periodic regime; (C) quasiperiodic with the main frequencies being the detuning and f_{ec} and harmonics

Figure 2 illustrates three representative optical spectra obtained for an injection ratio of $\kappa_{inj} = 1.1\ \%$. As the injection frequency is swept, we observe that for each detuning interval corresponding to the external-cavity frequency (2 GHz), the laser undergoes a sequence of bifurcations leading to quasiperiodic and possibly chaotic dynamics. These regimes are characterized by the coexistence of the detuning frequency, the external-cavity frequency f_{ec}, and harmonics, as shown in Figs. 2(a) and 2(c). Between these quasiperiodic windows, the laser shows periodic oscillations at the detuning frequency (Fig. 2(b)). Furthermore, the injection-locking boundary is no longer sharply defined but fragmented into regions of complex nonlinear behavior. This fragmentation weakens the stability of the locking zone and renders its precise identification more challenging.

1. Sciamanna & Shore. *Nature photonics*, *9*(3), 151-162 (2015)
2. Liao & Lin. Optics Express, 21(20), 23568 (2013)
3. Song *et al.* Optics Communications, 354, 213-217 (2015)
4. Nizette & Erneux. IEEE JSTQE, 10(5), 961-967 (2004)
5. Oliverio, Rontani & Sciamanna. Optics Express, 32(15), 25906-25918 (2024)