Bounded-phase chaotic dynamics in a vectorial laser

Aurélien Thorette, Marco Romanelli, Marc Brunel, Marc Vallet

Institut de Physique de Rennes, UMR Université Rennes I - CNRS 6251, Campus de Beaulieu, 35042

Rennes Cedex, France aurelien.thorette@univ-rennes1.fr

Bounded-phase dynamics, also called phase-trapping or frequency-locking without phase-locking, is a synchronization regime found when a phase-locked state bifurcates via a Hopf bifurcation to self-sustained phase and amplitude oscillations. After the instability, the coupled oscillators are not phase-locked anymore, yet they maintain frequency-locking and synchronization [1]. This phenomenon is rather universal, and has been demonstrated for instance in semiconductor and solid-state lasers, in hydrodynamics and in nanomechanical resonators. Recently, the relevance of these underdamped and self-sustained phase oscillations has also started to be investigated for the synchronization of quantum systems [2].

To date, observations of the bounded-phase regime have been limited to smooth, supercritical bifurcations. The aim of this contribution is to present an experiment in which a phase-locked state undergoes a subcritical bifurcation leading directly to a chaotic state. We demonstrate the existence of a regime characterized by chaotic phase and amplitude oscillations, and prove that frequency-locking can be maintained, i.e. that bounded-phase synchronization is possible also in the presence of chaotic dynamics. Furthermore, by measuring the phase noise spectrum of the oscillator, we show that the beat-note signal still keeps a good spectral purity at low frequencies, in spite of the chaotic phase oscillations [3].



Fig. 1 (a) Experimental setup. (b) Time series of the output intensity (blue) and phase (red) in the bounded phase chaotic regime. One can clearly see that the phase remains bounded in spite of the chaotic behavior. (c) Phase noise spectra. (Black: free-running laser, blue: phase-locked regime, green: regular bounded phase regime, red: chaotic bounded phase regime).

The experimental setup (Fig. 1a) consists in a Nd:YAG dual-frequency laser oscillating on two polarization modes of frequencies v_x and v_y . The x-mode is frequency-shifted by an acousto-optic modulator (AO) of an amount $2f_{AO}$ and injected back in the y-mode, so that, under appropriate conditions, the latter synchronizes on the injected frequency i.e. the optical interference signal synchronizes with an external radiofrequency (RF) oscillator. The injection strength and detuning can be chosen so that chaotic amplitude and phase oscillations are observed (Fig. 1b). However, the phase oscillations are comprised in the interval $[-\pi;\pi]$, so that the average frequency is still determined by the master oscillator. The measure of the phase noise spectra (Fig. 1c) allows to quantify this observation. With respect to the phase-locked (blue trace) and to the regular bounded-phase (green) states, in the bounded-phase chaotic regime (red) one observes the presence of broadband spectral features in the 1 kHz–100 kHz range, a signature of the chaotic dynamics. Nevertheless the low-frequency part of the spectrum is comparable to the phase-locked state: the phase noise at 100 Hz is the same in both cases (at least 30 dB lower than for the free-running oscillator), i.e. the phase displays chaotic oscillations around an average value which is locked to the master oscillator. As it is the case for the non-chaotic bounded phase regime, we expect this behavior to be generic for synchronizing systems. From the viewpoint of applications, it may be of interest for chaotic sensing.

References

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