Delay identification in semiconductor lasers with optical feedback

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Semiconductor lasers (SLs) with optical feedback have attracted a lot of attention in the chaos cryptography community due to its capability to develop broadband chaos within which giga-bit message can be encoded[1]. The security of laser-based chaos communications relies mainly on the difficulty of identifying the emitter parameters necessary to build an adequate receiver which can synchronize with it.

In chaos communication schemes based on SLs with delayed optical feedback, the delay time can be identified from time series using standard techniques in most parameter regimes. However, the efforts to enhance the security in these schemes have led to the characerization of a regime in which the delay time appears to be concealed, namely when it is closer to the relaxation period of the laser operating with moderate feedback[2]. These results were obtained exclusively by computing the quantifiers from intensity time series. Taking into account that, in addition to the intensity, the phase information is also transmitted through the public channel, it is mandatory to check if the delay time can be concealed when computing different quantifiers from the phase of the field.

Here, we show results for the analysis of time series that originate from a numerical realization of a SL with delayed optical feedback. The model is based on the Lang and Kobayashi rate equations, which are described in terms of the complex electric field $E(t)$ and the carrier number $N(t)$ inside the active layer (see[3] for details). The laser exhibits chaotic intensity pulsations in our numerical realization of a laser with optical feedback. In order to identify the time delay, we employ the autocorrelation function (ACF) and delayed mutual information (DMI) quantifiers. The time delay present in the system dynamics can then detected through the presence of clear extrema of the quantifiers when they are calculated as a function of a time lag.

In Fig. 1 we plot the autocorrelation function and the delayed mutual information obtained by analyzing the intensity time series, $|E(t)|^2$, for two different feedback strengths (κ) when the delay time T is close to the relaxation oscillation period τ_{RO}. The quantifers are not able to identify the delay time at $T = 1$ ns for $\kappa = 5$ ns^{-1}, see Fig 1 (a) and (c). In contrast, a clear peak at $T = 1$ ns can be observed for $\kappa = 10$ ns^{-1}, see Fig 1 (b) and (d).

The delay time can be concealed in the intensity time series when the laser is subject to a low feedback strength and $T \sim \tau_{RO}$. However, the phase information contained in the optical field emitted by the laser also needs to be analyzed. We present in Fig. 2 the autocorrelation function and the delayed mutual information obtained by analyzing time series from the phase and the real part of the electric field. Remarkably, the delay time can be identified both for low and moderate feedback strengths.

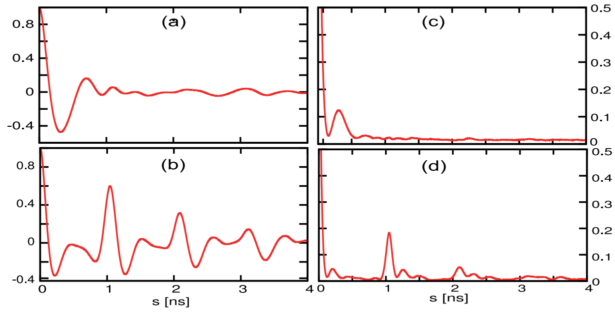

FIG. 1. ACF (left) and DMI (right) for $T = 1$ ns and $\tau_{RO} = 0.75$ ns (a, c) $\kappa = 5$ ns^{-1}, (b, d) $\kappa = 10$ ns^{-1}, obtained by analyzing the intensity time series.

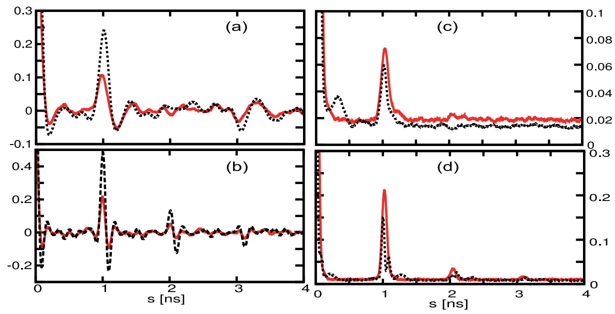

FIG. 2. ACF (left) and DMI (right) for $T = 1$ ns and $\tau_{RO} = 0.75$ ns (a, c) $\kappa = 5$ ns^{-1} , (b, d) $\kappa = 10$ ns^{-1}, obtained by analyzing time series from the phase (solid line) and the real part (dot line) of the complex electric field, respectively.

We have illustrated by means of the autocorrelation function and the delayed mutual information that, in semiconductor lasers with optical feedback, the time-delay signature can be better retrieved from the phase of the complex electric field rather than the intensity. Interestingly, not only the time delay peak is always distinguishable when computing the quantifiers from the phase, but its precise location is also considerably improved compared to the quantifiers obtained by analyzing the intensity time series[3].

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