Tuning the period of square-wave oscillations in delay-coupled opto-electronic systems

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We examine the emergence of stable square-waves in a system of two delay-coupled opto-electronic oscillators. Each oscillator operates under its own delayed feedback and the presence of two delays allows a large number of stable square-wave time-periodic regimes. By using asymptotic methods based on the relatively large values of the two delays, we propose a systematic analytical study of the bifurcation mechanisms. The validity of all our results is tested by solving numerically the original evolution equations for the opto-electronic oscillators. Because of the two distinct delays, the bifurcation possibilities are rich but their derivations are relatively simple because the analysis essentially relies on the solutions of coupled equations for maps. In this sense, we expect that our analysis can be applied to other two-delayed coupled systems and lead to similar results.

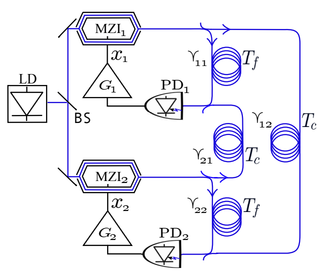

FIG. 1. Setup.

We consider two electro-optical delay systems[1] that are mutually coupled as shown in FIG.1. The light emitted by a cw semiconductor laser (LD) with intensity P is split into two beams, each beam feeding an electro-optical delay loop. Each loop consists of a Mach-Zehnder interferometer (MZI), an optical delay line, a photodiode (PD) and an amplifier. We use subindex i, $i = 1, 2$, to identify the variables associated to loop i. For loop i the optical output of MZI$_i$ is split into two parts. A fraction γ_{ii} is delayed using a fibre loop by a time T_{ii}. A fraction γ_{ij} with $i, j = 1, 2$ and $j \neq i$ is injected from loop i into loop j after a delay T_{ij}. Self-feedback and cross-feedback optical signals are combined and the resulting intensity is detected by the PD. The electrical signal goes through a band-pass amplifier and is finally used to drive the Mach-Zehnder AC electrode. For each loop, the dynamics results from a combination of the nonlinear effect due to the MZI plus a linear filtering process associated to the electrical part of the loop. The dynamics of the electrical signal x_i is:

$$x_i(t) + \tau_i \frac{dx_i}{dt}(t) + \frac{1}{\theta_i}\int_{t_0}^{t} x_i(s)ds = PC_i,$$

$$C_i = \gamma_{ii}^2\cos^2(z_{ii}) + \gamma_{ji}^2\cos^2(z_{ji}) + \\ + 2\gamma_{ii}\gamma_{ji}\cos(z_{ii})\cos(z_{ji})\cos(z_{ii} - z_{ji}),$$

where $i, j = 1, 2$, $z_{ji} = x_j(t - T_{ji}) + \phi_j$, $T_{ii} = T_f$, $T_{ji,j\neq i} = T_c$, and ϕ_i is an offset phase.

We show that this system can display square-wave periodic solutions which can be synchronized in-phase or out-of-phase depending on the ratio $s_0 = T_f/T_c$; in particular, the synchronization is in-phase if the ratio involves two odd numbers while it is out-of-phase for ratios involving an odd and an even number. Furthermore, multiple periodic synchronized solutions can coexist for the same values of the fixed parameters, as it is illustrated in FIG.2. As a consequence, it is possible to generate square-wave oscillations with different periods by just changing the initial condition.

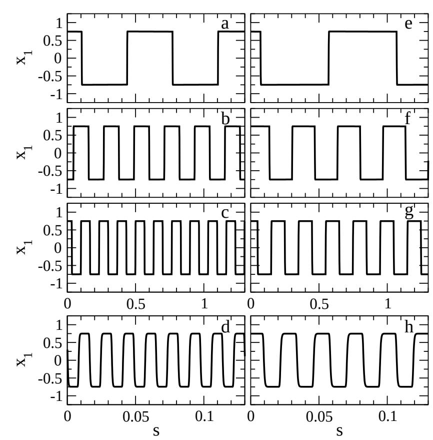

FIG. 2. Time trace of square-wave periodic solutions with $P = 1.5$, $\gamma_{ij} = 0.5$, $\phi = 0.25\pi$, and $T_f = 30ns$. The panels of the left column display coexisting in-phase solutions for $T_c = 90$ns ($s_0 = 1/3$). The panels of the right column display coexisting out-phase solutions for $T_c = 60$ns ($s_0 = 1/2$). In rows, fundamental solution (a, e), first harmonic (b, f), second harmonic (c, g), and twentieth harmonic (d, h). Notice that the time scale used in panels (d) and (h) is 10 times smaller than in the other panels. $s = t/T_c$ is the dimensionless time.

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