CHAOS-SYNCHRONIZATION IN SEMICONDUCTOR LASER SYSTEMS: AN OPTICAL PHASE DEPENDENT SCENARIO

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Abstract. Synchronization of chaotic oscillators is of high current interest in various areas of science. Semiconductor laser systems offer a great potential for experimental studies of synchronization phenomena, because of well-controllable parameters, well-studied nonlinear dynamical behavior and their broad spectrum of applications. We investigate chaos-synchronization of two unidirectionally coupled semiconductor lasers with delayed optical feedback. We present a characteristic synchronization scenario in dependence of the relative optical cavity phase of the subsystems. For adjusted phase, we find excellent synchronization of the intensity dynamics in combination with coherence among the emitted fields of the lasers, despite of the fast chaotic wavelength-fluctuations. Variation of the phase leads to conspicuous changes in the intensity-dynamics associated with drastically reduced correlation and loss of coherence among the lasers. Our results provide insight into the consequences of vectorial coupling for the synchronization scenario and open the perspective for innovative concepts for encrypted GHz data communication.

INTRODUCTION

Synchronization phenomena of coupled nonlinear oscillators are of fundamental interest, as they are encountered in various areas of science [1–3]. Recently, chaos synchronization phenomena of coupled chaotic semiconductor laser (SL) systems have attracted much attention, since their well-controllable parameters and their well-studied nonlinear behavior [4,5] makes them ideally suited for studies on the fundamental synchronization phenomena of coupled nonlinear systems. Furthermore, they enable the realization of innovative applications in the field of telecommunication, using chaotic carriers for encrypted high-bandwidth data transmission [6–10]. The understanding of the synchronization scenario related to variations of the system parameters is of high relevance for both aspects.

A particularity of SL systems is the possibility of vectorial coupling via amplitude and phase of the optical fields. We experimentally study the importance of this kind of coupling on the chaos synchronization scenario of two unidirectionally coupled SL systems, where each system is subject to delayed optical feedback, thus emitting chaotically [4,11,12]. We concentrate on the chaos synchronization scenario of these coupled systems in dependence of the well-controllable relative cavity phase and show that the vectorial nature of the optical coupling is of particular importance. For matched cavity-phase-conditions, we find excellent synchronization of the intensity dynamics in combination with constructively interfering fields of the lasers, hence coherence among the lasers. Varying the relative cavity phase, we find a characteristic scenario. We observe gradual loss of synchronization, conspicuous changes in the intensity dynamics associated with drastically reduced cross correlation coefficients, and loss of the coherence among the lasers. We demonstrate the stability of the synchronization manifold and provide perspectives for the functional use of these properties in innovative concepts for encrypted high-bit data communication.

EXPERIMENTAL RESULTS

A sketch of the experimental setup is depicted in Fig. 1. Our system consists of two SLs, subjected to delayed optical feedback ($\tau_d = 2.9\,\mathrm{ns}$) from high reflecting mirrors, thus emitting chaotically. Each laser is pumped by a DC low noise current source at 1.01 times its solitary threshold current I_{th}^{sol}, and is temperature stabilized to better than 0.01 K. We have selected two device-identical SLs, as coinciding laser parameters are essential for chaos synchronization. In order to avoid asymmetries with respect to detuning effects, we monitor the optical spectra of both lasers with an optical spectrum analyzer (OSA) with 0.1 nm resolution, such that their frequencies match within an accuracy to better than 1 GHz. By changing the length of the cavities on sub-wavelength scale via piezo translators (PZT), we vary the

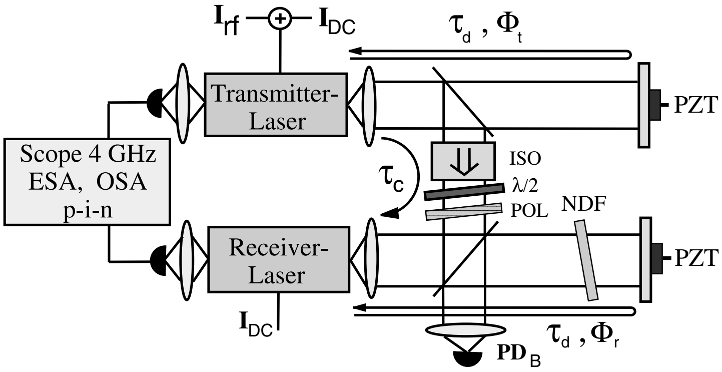

FIGURE 1. Experimental setup of coupled transmitter and receiver external cavity lasers.

feedback phase of the reflected light (cavity phase) $\Phi_{t,r}$. In the following, we will call the driving laser *transmitter* and the driven laser *receiver*. The unidirectional coupling is realized optically by injecting a well-defined fraction of the optical field of the transmitter via an optical isolator (ISO) into the receiver. The polarizer (POL) and the $\frac{\lambda}{2}$-plate guarantee a coupling via the dominant TE component of the optical field. We detect the intensity dynamics of both lasers simultaneously with photodetectors and an electrical spectrum analyzer (ESA). A 2-channel oscilloscope of 4 GHz analog bandwidth resolves the fast intensity fluctuations on the relevant sub-ns time scales and the low frequency fluctuations, which are the typical dynamical effects for these conditions (LFF) (see e.g. [11]). We couple an intensity equal to 40 % of the transmitters feedback intensity into the receiver, whose feedback intensity is reduced by a neutral density filter (NDF) to 70 % compared to the transmitters feedback intensity. For this condition, we achieve excellent synchronization of the intensity time series of the lasers [13]. We find that the relative cavity phase $\Phi_{rel} = \Phi_r - \Phi_t$ is a key parameter determining the intensity dynamics of the receiver. In this contribution we concentrate on the influence of Φ_{rel} by varying Φ_r. In Figure 2 we present intensity time series of the coupled systems for three dynamical regimes corresponding to different relative cavity phase conditions. In Fig. 2 a) $\Phi_{rel} = 0\,\pi$, in c) $0.7\,\pi$, and $1.4\,\pi$ in d). The time series of the transmitter

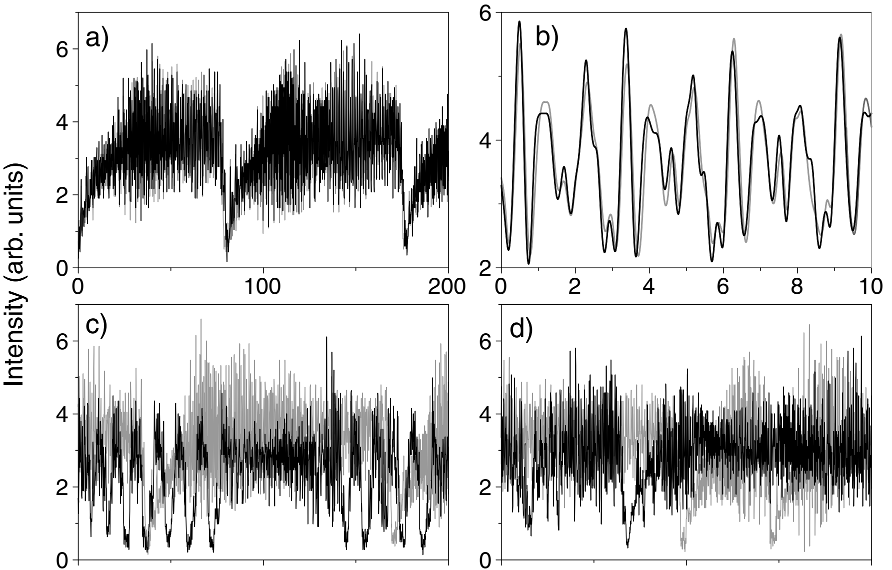

FIGURE 2. Intensity time series of the transmitter (grey solid line) and the receiver (black solid line) for various relative cavity phases: $\Phi_{rel} = 0\,\pi\,\mathrm{rad}$ a), $0.7\,\pi\,\mathrm{rad}$ c), and $1.4\,\pi\,\mathrm{rad}$ d). For ease of comparison the time lag of the receiver time series $\tau_c = 2.9\,ns$ has been compensated for. Figure b) depicts a 10 ns zoom of a). The parameters for the transmitter are kept constant for the different phase conditions.

and the receiver are represented by grey solid and black solid lines, respectively. Fig. 2 a) depicts the time series for optimized phase condition $\Phi_{rel} = 0\,\pi$. For this regime we observe excellent synchronization of the intensity dynamics of the transmitter and the receiver. We obtain a maximum cross correlation coefficient of 0.90 of the time series, if the time series of the receiver is shifted forward in time by the coupling time $\tau_c = 4.6$ ns [8,13]. For ease of comparison, the lag of the time series of the receiver has been compensated for in Fig. 2. We monitor the rf and the optical spectra of the transmitter and the receiver and find remarkable correspondence to each other, thus confirming the synchronization. Comparison of Fig. 2 a) and its 10 ns zoom Fig. 2 b), reveals that the time series are almost identical not only with respect to the intensity dropouts, but even more on the dynamically relevant sub-ns time scales. We find that the synchronization is independent of the coupling time τ_c and robust against small variations of the injection current and the coupling strength. Next we vary the relative cavity phase from $\Phi_{rel} = 0$ to $\Phi_{rel} = 2\,\pi$ and monitor the influences on the the emission dynamics of the receiver. We observe intermittent loss of synchronization with still high correlated intervals of the time series, leading to slowly decreasing correlation coefficients. Reaching $\Phi_{rel} = 0.7\,\pi$, we find drastic changes in the intensity dynamics of the receiver. Figure 2 c) depicts the intensity time series for this striking regime. The still highly correlated intervals have vanished and we observe well pronounced intensity oscillations in combination with a strong decrease of the correlation coefficient down to 0.2. For this regime, the optical spectra of the transmitter and the receiver show deviations in their relative intensities of the longitudinal modes. Increasing Φ_{rel} further to $\Phi_{rel} = 1.4\,\pi$, the strong oscillations in the intensity dynamics of the receiver vanish, and the transmitter and receiver seem to run independently. The corresponding time series are depicted in Figure 2 d). The correlation coefficient for the time series has decreased to 0.1. Further increasing Φ_{rel} up to $2\,\pi$, we regain synchronization passing through a steep increase of the correlation coefficients. We find that Φ_{rel} is a $2\,\pi$ periodic parameter for variations of the cavity length within a range of several wavelengths. In order to get more detailed insight into the properties of the coupling conditions, we measure the intensity at the photodetector PD_B. We find low intensities for the synchronization regime, due to constructive interference of the coupling field and the feedback field of the receiver, hence the lasers couple coherently, despite of their fast wavelength-fluctuations. For low correlated states, corresponding to $1.2\,\pi < \Phi_{rel} < 1.6\,\pi$, we neither find constructive nor destructive interference effects, hence in these states the coupling field and the receiver feedback field are incoherent. An overview over the the synchronization scenario depending on Φ_{rel} represented by the cross correlation coefficient for the intensity time series of the transmitter and receiver is depicted in Fig. 3. We note that the figure exhibits asymmetries for the correlation coefficients in dependence of Φ_{rel}, since the coefficients for Φ_{rel} differ significantly from those for $\Phi'_{rel} = 2\,\pi - \Phi_{rel}$.

In order to verify the existence of a stable synchronization manifold and to distinguish the observed behaviour from linear amplification, we apply a perturbation to the DC pump current of the transmitter by adding a small sinosoidal AC mod-

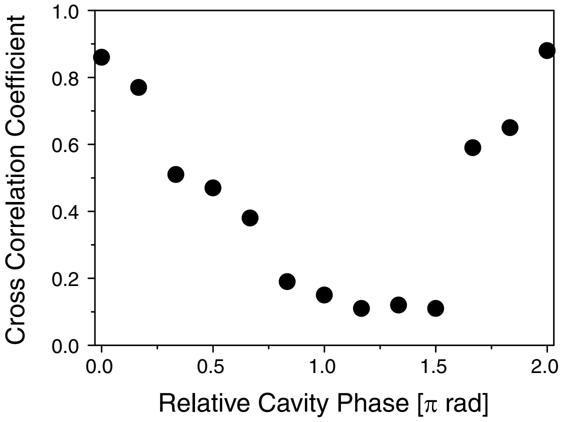

FIGURE 3. Cross correlation coefficients of the intensity time series of the transmitter and receiver with respect to the relative cavity phase Φ_{rel}.

ulation of approximately 1 % of I_{th}^{sol}. We analyze the behaviour by monitoring the rf spectra of both lasers. For a stable synchronization manifold, the system should exhibit chaos pass filtering properties [8], which means that a small perturbation superimposed onto the driving system is suppressed by the driven system. Figure 4 depicts the rf spectra of the transmitter and the receiver, represented by the grey and the black solid line, respectively. For clarity the spectrum of the transmitter is shifted vertically. The broadened peaks in the spectra correspond to the chaotic emission of the SL systems and are remarkably similar for the transmitter and the receiver. In this experiment the frequency of modulation has been chosen to 300 MHz. The peak, corresponding to the modulation frequency of the transmitter, is suppressed by 10 dB in the receiver. We could achieve up to 20 dB signal suppression for frequencies up to 2 GHz. We note that the suppression depends on the

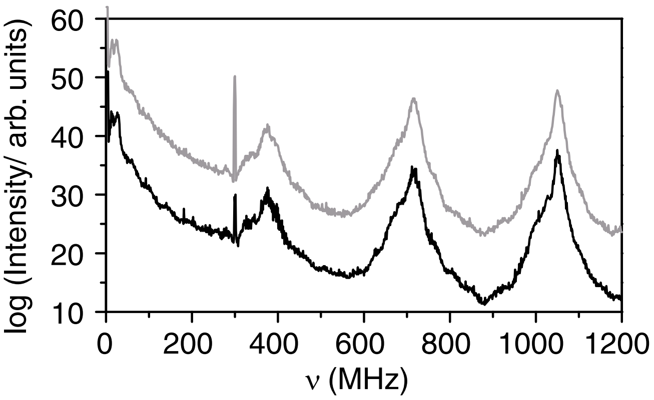

FIGURE 4. rf spectra of the intensity time series of the transmitter (grey line) and the receiver (black line). Frequency of pump current modulation for the transmitter is 300 MHz.

frequency of modulation. These results show that the synchronization manifold is stable. For Φ_{rel} deviating significantly from zero, we did not observe signal suppression, as synchronization of the lasers brakes down. This combination of excellent signal suppression at high frequencies, plus the high dimensional chaotic dynamics are very interesting for utilizing them in a high-bit rate encrypted communication system based on chaotic carriers.

SUMMARY

We have reported chaos synchronization for two unidirectionally optically coupled external cavity semiconductor lasers. We have classified four regimes of receiver's intensity dynamics depending on the relative cavity phases, i.e. synchronization, intermittent synchronization, large intensity oscillations, and uncorrelated intensity dynamics of the lasers. We find coherent emission of the optical fields of the two lasers for the synchronized state, despite of the fast wavelength-fluctuations. In contrast, for low correlated states the lasers are incoherent. Finally, we have demonstrated highly selective chaos pass filtering properties for our experiment, which make our receiver system attractive for the realization of innovative concepts for encrypted high-bit data communication utilizing chaos synchronization phenomena.

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