ON/OFF Phase Shift Keying for Chaos-Encrypted Communication Using External-Cavity Semiconductor Lasers

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Invited Paper

***Abstract*—Synchronization phenomena of two chaotically emitting semiconductor lasers subject to delayed optical feedback are investigated. The lasers are unidirectionally coupled via their optical fields. Our experimental and numerical studies demonstrate that the relative optical feedback phase is of decisive importance: a characteristic synchronization scenario evolves under variation of the relative optical-feedback phase mediating cyclically between chaos synchronization in conjunction with coherent fields, and uncorrelated states in conjunction with incoherent fields. As a key result, we propose, and numerically demonstrate, a novel ON/OFF phase shift keying method opening up new perspectives for applications in communication systems using chaotic carriers.**

***Index Terms*—Chaos, communications, optical feedback, semiconductor laser, synchronization.**

I. Introduction

COMMUNICATION systems using chaotic carriers can be considered as a generalization of the existing conventional communication systems, and exhibit a potential for private communication. In conventional communication systems, the message is modulated in the transmitter upon a periodic carrier, and the receiver then has to be tuned to this carrier frequency in order to recover the message. The chaotic carrier communications scheme generalizes this principle. Here, the message is modulated within the chaotic signal of the transmitter. Thus, similar to a spread-sheet communications approach, a broad spectrum of frequencies is used as a carrier for the information instead of a single frequency. The key for message recovery is the phenomenon of chaos synchronization. The receiver has to be tuned, i.e., synchronized, to the chaotic signal of the transmitter to extract the message. This method offers the following advantages for applications in enhanced privacy communications. First, the message is transformed within the carrier in a nonlinear dynamical process providing a dynamical key inherent to the transmission of the message. In this context, we note that a series of different encoding schemes have already been introduced: chaotic masking, shaos modulation keying, chaos shift keying, and ON/OFF shift keying (see [1] and references therein). Second, the message is concealed by the large amplitude and broad frequency range of the carrier signal. Finally, chaos synchronization is only possible if the transmitter and receiver are (almost) identical chaotic systems. Thus, privacy is enhanced by restricting the message recovery to persons owning an appropriately operated "chaos twin" of the transmitter. The application of chaos synchronization for private communication was suggested for the first time by Pecora and Caroll in 1990 [2]. In order to hinder eventual message recovery by eavesdroppers using advanced time-series analysis tools, scientific interest has focused on chaotic systems exhibiting high-dimensional and fast dynamics. In particular, laser systems naturally combine these two requirements in an excellent way. Already in 1994, synchronization in laser systems was demonstrated in CO_2 lasers [3], and in Nd:YAG lasers [4]. A first breakthrough concerning the speed and the dimension of the synchronized chaotic dynamics was achieved by VanWiggeren and Roy using fiber lasers [5], [6]. Currently, the semiconductor laser (SL) is probably the laser type with the highest potential for a practical realization of communication systems using chaotic carriers. The SL ideally combines the advantages of fast and high-dimensional chaotic dynamics, cost efficiency, simple configuration, and compatibility with already existing optical communication systems. These advantages of SLs for communication systems using chaotic carriers have prompted great scientific interest in recent years: synchronization in SLs has already been demonstrated numerically in laterally coupled lasers [7], and in spatially separated lasers [8]. Experimentally, synchronization of wavelength chaos [9], [10], synchronized low-frequency fluctuations (LFF) [11]–[14], and even slower intensity fluctuations [15], have already been observed. In particular, SLs subject to delayed optical feedback are a particularly straightforward configuration in order to obtain subnanosecond chaotic oscillations which, common to most delay systems, exhibit a very high dimensionality, e.g., the number of positive Lyapunov exponents

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present in the LFF dynamics has been numerically estimated to be very large [16]. Nevertheless, we are aware that a strong nonlinearity and a fast loss of correlation can be even more important than a high dimension in order to maximize the privacy of a communication system [17]. Accordingly, the fully developed coherence collapse (CC) [18] state in which the correlation decays rapidly is more suitable for communications applications than the LFF state, in which correlations are maintained for several delay times. In this paper, we investigate a configuration in which both the transmitter and receiver consist of a SL subject to delayed optical feedback from an external cavity of equal length showing chaotic dynamics, both in intensity, and wavelength. The unidirectional coupling between the subsystems is accomplished by injecting the dominant transverse electric (TE) component of the optical transmitter field into the receiver cavity. This configuration is commonly referred to as a closed-loop scheme, in order to distinguish it from the so-called open-loop scheme in which the receiver consists of a solitary SL. Though the open-loop scheme appears to be the more suitable for practical applications due to its simple configuration and robustness, we demonstrate in this paper that the closed-loop scheme offers additional possibilities which are of high interest for practical applications. To understand this, it is important to note that the optical field as a coupling parameter is a two-component vector consisting of the optical field amplitude and the optical phase. The influence of the coupling field amplitude, i.e., the coupling strength, on the synchronization behavior of the system has been studied numerically in [19], and experimentally for the open-loop scheme [20]. However, the influence of the relative feedback phase has been neglected until very recently [21]. In this paper, our experimental and numerical studies demonstrate that a well-controlled variation of the relative optical feedback phase $\Delta\Phi$ leads to a striking dynamical synchronization scenario mediating between chaos synchronization, and weakly correlated states. For adjusted phase, we achieve excellent synchronization for the intensity dynamics of transmitter and receiver in conjunction with the coherence of the optical fields. Variation of $\Delta\Phi$ leads to conspicuous changes of the receiver dynamics associated with a drastically reduced correlation in conjunction with incoherent optical fields. Finally, synchronization is regained for a phase shift of $\Delta\Phi = 2\pi$ underlining the cyclic character of the control parameter. This key relevance of $\Delta\Phi$ for the synchronization behavior of the system is particularly remarkable, as we do not observe an influence of $\Delta\Phi$ on the chaotic dynamics of the solitary subsystem, i.e., we do not detect changes in the transmitter signal under variation of the transmitter feedback phase, neither in the (time averaged) optical spectrum, nor in the intensity time series, nor in the corresponding RF spectrum. However, the receiver very sensitively detects these phase changes which determine its synchronization behavior. As a consequence of our results, we propose a new ON/OFF phase shift keying method for enhanced privacy communications applications. In this scheme, the message bits "0" and "1" correspond to two different values of the transmitter feedback phase. These phase changes switch on and off the synchronization between the transmitter and the appropriately operated receiver. This allows a straightforward and private recovery of the message via the synchronization error. However, as already mentioned above, we are not able to detect these transmitter phase changes without using the appropriate receiver. Accordingly, a recovery of the message by an an eventual eavesdropper from the time series alone appears to be difficult, noting that it is unclear whether an extraction of the transmitter phase shift from the time series is possible at all. The paper continues in Section II, presenting the experimental setup, and our experimental results. Section III introduces the rate equation model, and its results in comparison to the experiments. In particular, we first give numerical evidence for the feasibility of the novel ON/OFF chaos shift keying method. Finally, Section IV provides a short summary and presents our conclusions.

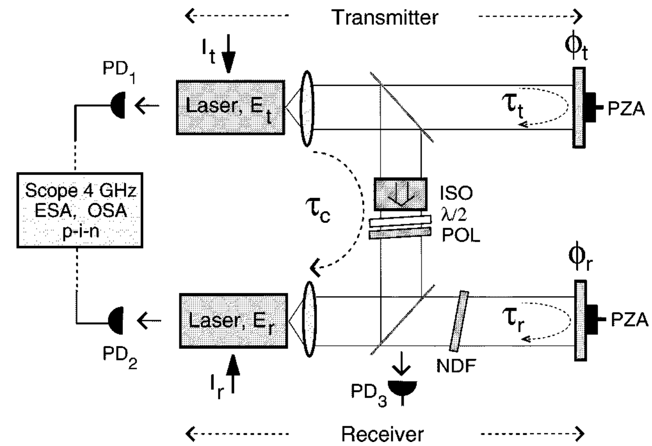

Fig. 1. Schematic representation of two unidirectionally coupled chaotic external-cavity semiconductor lasers and the detection setup.

II. Experimental Results

Fig. 1 depicts a scheme of the experimental setup. The lasers are two device-identical uncoated Hitachi HLP1400 Fabry–Perot SLs operating at 840 nm whose optical spectra agree within 0.1 nm, slope efficiency within 3%, and threshold current $I_{\rm th}^{\rm sol}$ within 7%. The SLs are pumped by low-noise dc current sources, and temperature stabilized to better than 0.01 K. Each laser is subject to delayed optical feedback from a distant gold mirror. The corresponding external-cavity delay times are carefully adjusted, and amount to $\tau_t = \tau_r = \tau_f = 2.9$ ns in both lasers. The optical feedback phases $\Phi_{t,r}$ are controlled individually in each subsystem by precision piezo actuators (PZA) changing the lengths of the external cavity on subwavelength scale. These two systems are coupled by injecting a well-defined fraction of the transmitter optical field into the external cavity of the receiver. An optical isolator (ISO), $\lambda/2$ plate, and polarizer (POL) guarantee a unidirectional coupling via the dominant TE component of the optical field. The coupling time τ_c amounts to 4.6 ns, though we note that τ_c is not relevant as the coupling is unidirectional. We resolve the intensity dynamics of the transmitter and receiver simultaneously on the subnanosecond time scale by combining two 6-GHz photodetectors ($PD_{1,2}$) with a fast digital oscilloscope of 4-GHz analog bandwidth on each channel, and an electrical spectrum analyzer (ESA). Furthermore, we monitor the optical spectra using an optical spectrum analyzer (OSA) with 0.1-nm resolution, and detect the average output power ($PD_{1,2,3}$). We choose the experimental conditions such that the transmitter

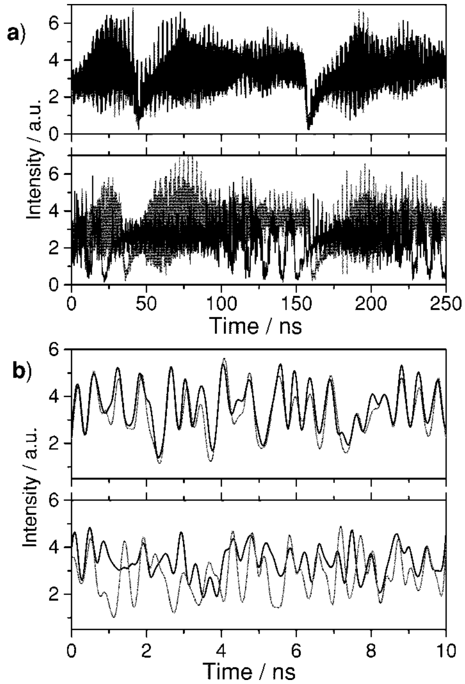

Fig. 2. Synchronization behavior of transmitter intensity (grey line), and receiver intensity (black line) in dependence on the relative optical feedback phase $\Delta\Phi$. (a) LFF operation with $I_{t,r} = 1.01\, I_{\mathrm{th,sol}}$. (b) CC operation with $I_{t,r} = 1.15\, I_{\mathrm{th,sol}}$. The upper panels in each subplot correspond to adjusted phase $\Delta\Phi = 0$, the lower panels correspond to $\Delta\Phi = 0.7\pi$.

and receiver operate in the well-studied LFF regime [22] for a pumping current of $I = 1.01\, I_{\mathrm{th}}^{\mathrm{sol}}$, and in the fully developed CC regime for $I = 1.15\, I_{\mathrm{th}}^{\mathrm{sol}}$, respectively. The amount of delayed optical feedback is controlled using the neutral density filter (NDF), leading to a threshold reduction of 7% in the transmitter and to 4% in the solitary receiver. We point out that all results presented in this paper are robust against reasonable variations of both the injection current and the feedback strength. For best synchronization results, it is necessary to minimize the detuning between the optical frequencies of the two lasers to less than 1 GHz by controlling the temperature of each laser appropriately. In addition, we find in agreement with [13] that synchronization is best when the sum of coupling and feedback intensity in the receiver is larger than the feedback intensity of the transmitter. For optimized conditions, we inject into the receiver laser 40% of the feedback intensity the transmitter is subject to, while the receiver feedback intensity is reduced by the NDF to 70% of the transmitter feedback intensity. In our experiments, we focus on the synchronization behavior of the system under variation of the relative optical feedback phase $\Delta\Phi$. This parameter can either be changed by variation of the receiver feedback phase Φ_r, or variation of the transmitter feedback phase Φ_t. Here, we restrict ourselves to changing $\Delta\Phi = \Phi_t - \Phi_r$ via Φ_t as this would be the case in a possible chaotic carrier communications system.

A. Synchronization

Fig. 2(a) and (b) depicts snapshots of the intensity time series of both coupled lasers for two different values of the relative optical feedback phase $\Delta\Phi$ under LFF conditions and under fully developed CC conditions, respectively. The upper panels depict the time series for optimized synchronization between the transmitter and receiver. We assign the relative optical feedback phase to $\Delta\Phi = 0$ under these conditions, a choice being confirmed in the following by our numerical simulations. The lower panels correspond to $\Delta\Phi = 0.7\pi$. Fig. 2 demonstrates that for $\Delta\Phi = 0$, we achieve excellent synchronization, both under CC operation and under LFF operation. In the LFF regime, we note that not only the slow intensity drop-outs, but also the fast subnanosecond intensity fluctuations are highly correlated. In both regimes, we find maximum cross correlation between the two signals if the receiver time series is shifted forward in time by τ_c. Thus, as observed previously, the signal of the receiver is lagging in the synchronized state by the coupling time τ_c [11], [13]. Accordingly, due to this fixed time lag and the nonsymmetrical feedback and coupling conditions, we do not observe identical synchronization here, but generalized synchronization [23]. Nevertheless, we observe a cross-correlation coefficient as large as 0.9, provided the time lag of the receiver time series is compensated for. Fig. 2 depicts such time series in which the receiver time series has been shifted forward in time by τ_c in order to ease the comparison. Further investigating the synchronization, we monitor the radio frequence (RF)-spectra and the optical spectra of transmitter and receiver. We find excellent agreement of RF and optical (multimode) spectra, both under LFF and CC conditions, hence confirming the synchronization. However, the lower panels of Fig. 2(a) and (b) demonstrate that the receiver dynamics drastically changes when we set $\Delta\Phi = 0.7\pi$. Synchronization is lost both in the LFF, and in the CC regime. Time series, RF spectra, and optical spectra of the receiver are now clearly different from the transmitter which appears to be unaffected. Particularly remarkable are the strong, low-frequency intensity fluctuations of the receiver shown in Fig. 2(a) (lower panel) which occur in the vicinity of a transmitter intensity drop-out. In the following, we investigate this transition from synchronization to uncorrelated states in more detail.

B. Synchronization Scenario for Variation of $\Delta\Phi$

As soon as $\Delta\Phi$ deviates sufficiently from zero, we find a sudden switching behavior between time intervals of synchronization with highly correlated dynamics of the two lasers, and time intervals of desynchronized low correlated states. These jumps occur more frequently for increasing $\Delta\Phi$. Accordingly, the maximum cross correlation between receiver and transmitter intensity time series decreases for increasing $\Delta\Phi$ until, finally, synchronization is not observed anymore. Thus, our experiments demonstrate that a gradual variation of $\Delta\Phi$ away from optimized synchronization leads to temporal alternation in the synchronization behavior of the system. Further increasing $\Delta\Phi$ toward 2π, we find that synchronization is regained. As expected, the relative optical feedback phase $\Delta\Phi$ turns out to be a cyclic parameter for variation of the cavity length within a range of a few wavelengths. In order to quantify the above observations, and to summarize the synchronization scenario, we calculate the maximum time-averaged correlation coefficient Σ_{corr} and its dependence on $\Delta\Phi$ from the experimental data. We define Σ_{corr} as follows:

$$\Sigma_{\mathrm{corr}} = \max_{\tau} \left\{ \frac{\langle \delta P_t(t) \delta P_r(t-\tau) \rangle}{\sqrt{\langle \delta P_t^2(t) \rangle \langle \delta P_r^2(t-\tau) \rangle}} \right\} \tag{1}$$

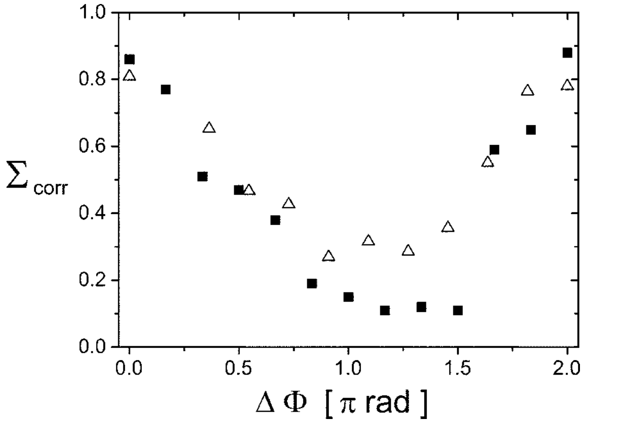

Fig. 3. Experimental cross-correlation coefficients of the intensity time series of transmitter and receiver versus the relative optical feedback phase $\Delta\Phi$ under LFF operation ($I_{t,r} = 1.01\, I_{\rm th,sol}$, solid squares), and CC operation ($I_{t,r} = 1.15\, I_{\rm th,sol}$, open triangles), respectively.

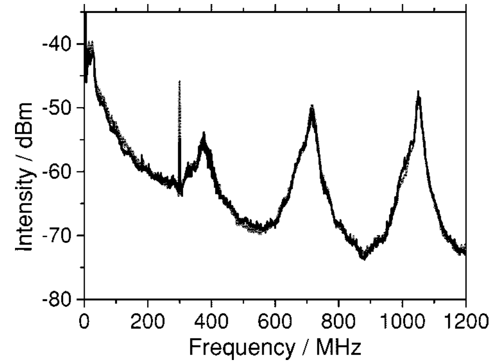

Fig. 4. Experimental RF spectra of the synchronized ($\Delta\Phi = 0$) transmitter signal (grey line), and receiver signal (black line) under LFF operation ($I_{t,r} = 1.01\, I_{\rm th,sol}$) showing the response of the subsystems on small sinusoidal modulation of the transmitter. The frequency of the modulation is 300 MHz, and the amplitude is $0.01\, I_{\rm th,sol}$.

where $P_{t,r}(t)$ are the transmitter and receiver intensities, respectively, and $\delta P_{t,r}(t) = P_{t,r}(t) - \langle P_{t,r} \rangle$. Thus, the intensity dynamics is correlated when $\Sigma_{\rm corr} \approx 1$, while it is uncorrelated when $\Sigma_{\rm corr} \approx 0$. The parameter τ is introduced in order to account for the time lag between the transmitter and receiver signals. We always find that $\tau = \tau_c$ maximizes $\Sigma_{\rm corr}(\tau)$, as long as this maximum value exceeds $\Sigma_{\rm corr} \geq 0.5$. Fig. 3 provides an overview of the synchronization scenario by plotting $\Sigma_{\rm corr}$ as a function of $\Delta\Phi$ for LFF operation (solid squares) and for fully developed CC operation (open triangles). For both dynamical regimes, we find qualitatively the same behavior. Fig. 3 displays high correlation coefficients for adjusted phase $\Delta\Phi \approx 0$, where the regime of chaos synchronization is located. With gradually increasing $\Delta\Phi$, the correlation slowly decreases. The minima of $\Sigma_{\rm corr}$ are reached in the interval around $1\pi < \Delta\Phi < 1.4\pi$. Subsequently, the correlation steeply increases until chaos synchronization is regained for $\Delta\Phi \approx 2\pi$. It is important to note that both curves are asymmetric with respect to $\Delta\Phi$, i.e., $\Sigma_{\rm corr}(\Delta\Phi) \neq \Sigma_{\rm corr}(2\pi - \Delta\Phi)$. This is plausible since the rate equation model to be detailed in the numerical part of the paper shows that the equations are not invariant against substitution of $\Phi_{\rm rel}$ by $-\Phi_{\rm rel}$.

C. Synchronization and Optical Coherence

In order to investigate whether even coherence of the optical fields is associated with the synchronization of the intensity dynamics, we monitor the average intensity at the loss exit of the coupling beam splitter in the receiver cavity using PD_3. Doing this, we analyze interference effects between the coupling field and the field in the receiver cavity. We find that the average power at PD_3 in the synchronized state is significantly lower than in the less correlated states. This power reduction is due to destructive interference at PD_3, thus giving evidence for constructive interference of the two optical fields toward the receiver laser. Accordingly, the optical coupling field coming from the transmitter, and the receiver field inside the external cavity, are coherent. This coherence in the synchronized state is remarkable, as it occurs despite the fast chaotic fluctuation of the optical wavelength associated with the intensity dynamics of the subsystems. For the less correlated states, however, our experiment shows that the two optical fields add predominantly incoherently. Hence, we do not observe destructive interference toward the receiver laser under desynchronized operation.

Besides the coherence of the optical fields, the nonlinear chaos-pass filtering properties are another experimental measure for the synchronization behavior of the system. These chaos-pass filtering properties are closely linked to the communications applications to be discussed in the following subsection.

D. Synchronization and Communication

Nonlinear chaos-pass filtering properties allow one to distinguish between dynamical chaos synchronization and mere linear amplification [11]. In chaos synchronization, a small perturbation eventually present in the transmitter signal is filtered out by the receiver which selectively synchronizes to the transmitter chaos only. In contrast, a linear amplifier will amplify the chaotic signal, and the perturbation in the same way. In order to check these chaos-pass filtering properties in the present experiment, we impose a small sinusoidal modulation ($\approx 0.01\, I_{\rm th}^{\rm sol}$) upon the dc injection current of the transmitter, and observe the response of the receiver laser. Fig. 4 depicts the RF spectra of the transmitter (grey), and the receiver (black) under synchronized LFF operation. The modulation peak at 300 MHz is clearly visible in both spectra. However, the peak in the receiver spectrum is strongly damped by approximately 10 dB, whereas all other frequencies belonging to the chaotic broad-band emission spectrum of the transmitter are perfectly reproduced. Thus, the receiver selectively filters out the external modulation evidencing a genuine dynamical synchronization process. For optimized synchronization, we observe a suppression of the external perturbation of up to 20 dB for modulation frequencies from 50 MHz up to 2 GHz. As expected, we cannot observe this chaos-pass filtering as soon as $\Delta\Phi$ deviates sufficiently from zero, leading to a substantial reduction of the correlation between the time series. The nonlinear chaos-pass filtering and the high suppression ratios demonstrated in Fig. 4 exhibit a great potential for practical applications in chaotic carrier communications. In this approach, the message is modulated within the transmitter signal representing the chaotic carrier, embedded within, and hidden by the chaotic oscillations. The message is extracted by comparing the synchronized signal of the receiver with the incoming transmitter signal. We note that this method has already been demonstrated using SLs in an open-loop configuration [11] though with somewhat smaller suppression ratios. Yet our investigations revealing the decisive importance of the optical feedback phase in the closed-loop configuration open up additional new perspectives for chaotic carrier communications using SLs, which we present in the following subsection.

E. ON/OFF Phase Shift Keying

We propose a new chaotic carrier communications scheme which is based on the results presented in this paper. We call this new scheme ON/OFF phase shift keying. The physical basis for this novel chaotic carrier communication scheme is our discovery that the synchronization behavior of the receiver acts as a sensitive detector for variations of the transmitter feedback phase Φ_t: suitable discrete changes of Φ_t directly translate to changes of $\Delta\Phi = \Phi_t - \Phi_r$ which, in turn, switch the receiver dynamics between synchronized and de-synchronized states. In contrast to these drastic changes in the receiver dynamics, we do not detect effects due to variations of Φ_t in the transmitter signal itself, neither in the intensity dynamics, nor in the RF spectra, nor in the optical spectra. Accordingly, the principle of the proposed ON/OFF phase shift keying is as follows. The message is encoded by two different values of Φ_t switching between synchronized states (Bit "0") and less correlated states (Bit "1") in an appropriately operated receiver system. Hence, message recovery is easily accomplished by monitoring the synchronization error. These controlled variations of Φ_t can be accomplished by inserting an electrooptical modulator within the external cavity of the transmitter. In the following numerical part of this paper, we will first give evidence for the feasibility of this novel ON/OFF chaos shift keying scheme for private communications applications. We begin with a brief description of the rate equation model.

III. Numerical Results

We model the transmitter and receiver system by means of rate equations for the complex slowly varying amplitudes of the electric fields $E_{t,r}$ and the carrier numbers $N_{t,r}$ within each SL, where single-mode operation of the lasers is assumed [24]. The subscripts t, r stand for the transmitter and receiver system, respectively. Accordingly, the rate equations governing the optical and material variables read

$$\dot{E}_t(t) = \frac{1}{2}(1+i\alpha)\left[G_t - \gamma\right] E_t + \kappa_t e^{-i(\Omega\tau_t + \Phi_t)} E_t(t-\tau_t) + \sqrt{2\beta\gamma_e N_t}\,\xi_t(t) \tag{2}$$

$$\dot{E}_r(t) = \frac{1}{2}(1+i\alpha)\left[G_r - \gamma\right] E_r + \kappa_r e^{-i(\Omega\tau_r + \Phi_r)} E_r(t-\tau_r) + \sqrt{2\beta\gamma_e N_r}\,\xi_r(t) + \kappa_c e^{-i\Omega\tau_c} E_t(t-\tau_c) \tag{3}$$

$$\dot{N}_{t,r} = \frac{I_{t,r}}{e} - \gamma_e N_{t,r} - G_{t,r}|E_{t,r}|^2 \tag{4}$$

$$G_{t,r} = \frac{g(N_{t,r} - N_0)}{1 + \varepsilon|E_{t,r}|^2}. \tag{5}$$

We assume that both SLs have equal intrinsic parameters, in addition to an identical free-running emission frequency Ω. The first terms on the right-hand of the field (2) and (3) are the contribution of the solitary lasers (gain-loss balance). The second terms account for the external optical feedback, with external cavity round-trip times $\tau_{t,r}$, and feedback rates $\kappa_{t,r}$, respectively. Multiple round trips of the light in the external cavities are neglected. The phases accumulated by the electric field in a round-trip of the external cavity are $\Phi_{t,r} = \Omega\tau_{t,r}\ (\mathrm{mod}2\pi)$. The last term in (3) describes the unidirectional injection of the optical transmitter field into the receiver. We note that the coupling time τ_c can be compensated for by redefining the local time in the receiver system, and the phase $e^{-i\Omega\tau_c}$ by simply re-scaling the transmitter field E_t. Thus, we can take $\tau_c = 0$ and $\Omega\tau_c \bmod 2\pi = 0$ without loss of generality. Finally, complex Gaussian random terms $\xi_{t,r}(t)$ are added in the field equations in order to model spontaneous emission processes. These numbers have zero mean $\langle\xi_{t,r}(t)\rangle = 0$ and correlation $\langle\xi_a(t)\xi_b^*(t')\rangle = 2\delta_{a,b}\delta(t-t')$, with $(a,b) = t, r$. The gain function in the carrier (4) is approximated by a linear dependence on the carrier number, accounting also for gain-suppression effects [(5)]. The meaning and numerical value of the remaining parameters can be found in Table I. The choice of parameter values is based on previous work, and typical of numerical modeling of this type of SL dynamics. A quantitative modeling of the specific laser type used in the experiments is not intended. In this paper, we focus on a situation where the external cavity round-trip lengths of the transmitter and receiver systems coincide. Thus, we consider the delay time to be fixed at $\tau_f = \tau_t = \tau_r$, but we allow for the relative feedback phase $\Delta\Phi = \Phi_t - \Phi_r \in [0, 2\pi]$. The crucial relevance of the relative feedback phase on the dynamical behavior of the receiver and the synchronization properties will be discussed in the following. We consider feedback-induced instabilities that arise in the long-cavity regime. We choose $L_e = 45$ cm, corresponding to a delay time of $\tau_f = 3$ ns. For the sake of simplicity and numerical purposes, we rescale the dynamical variables by means of

$$A_{t,r} = \sqrt{\frac{g}{\gamma_e}}E_{t,r}, \qquad D_{t,r} = \frac{N_{t,r}}{N_0} - 1. \tag{6}$$

We also express the injected current as $p_{t,r} = I_{t,r}/I_{\mathrm{th}}^{\mathrm{sol}}$, with $I_{\mathrm{th}}^{\mathrm{sol}}$ being the threshold current of the free-running lasers. In this paper, we focus on the case of two equally pumped lasers, i.e., $p_t = p_r$.

TABLE I
DEVICE AND PHYSICAL PARAMETERS

Symbol	Meaning	Value
α	linewidth enhancement factor	5
g	differential gain	$6 \times 10^{-6}\mathrm{ns}^{-1}$
γ	cavity decay rate	$200\mathrm{ns}^{-1}$
γ_e	electron decay rate	$2\mathrm{ns}^{-1}$
N_0	transparent carrier number	1.5×10^8
ϵ	gain suppression coefficient	5×10^{-7}
β	spontaneous emission factor	10^{-7}
τ_f	external cavity roundtrip time	3ns
I_{th}^{sol}	solitary threshold current	≈ 60 mA

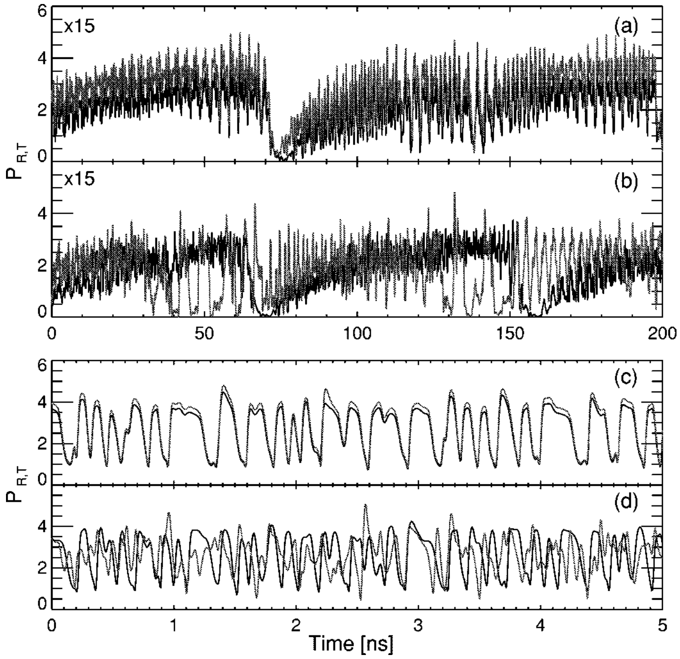

Fig. 5. Temporal evolution of the optical power $P_{T,R} = |A_{T,R}|^2$ in the: (a), (b) LFF regime $p_t = p_r = 1.0$ and (c), (d) CC regime $p_t = p_r = 1.5$. Solid lines: transmitter. Grey lines: receiver. Parameters: (a), (c) $\kappa_t = \kappa_c = \kappa_r = 20\ \mathrm{ns}^{-1}$, $\alpha = 4$, $\Delta\Phi = 0$ and (b), (d) $\Delta\Phi = \pi$.

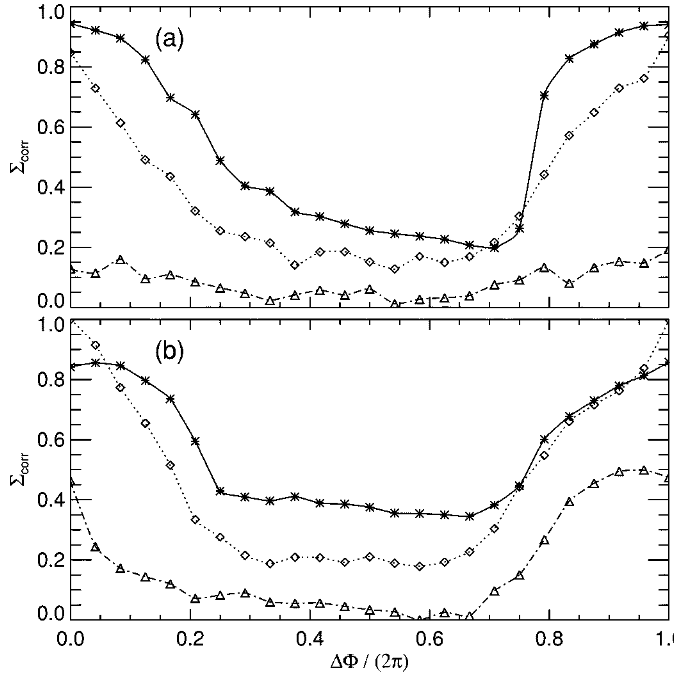

Fig. 6. Calculated cross-correlation coefficient Σ_{corr} as a function of the relative phase $\Delta\Phi$ for different receiver feedback strengths. (a) LFF regime with $p_t = p_r = 1.01$. (b) CC regime with $p_t = p_r = 1.5$. Other parameters: $\Phi_t = 0$, $\Phi_r = \Delta\Phi$, $\kappa_t = 20\ \mathrm{ns}^{-1}$, $\kappa_c = 20\ \mathrm{ns}^{-1}$, and $\kappa_r = 10\ \mathrm{ns}^{-1}$ ($*$), $\kappa_r = 20\ \mathrm{ns}^{-1}$ ($\Diamond$), $\kappa_r = 30\ \mathrm{ns}^{-1}$ ($\triangle$).

A. Synchronization

In this subsection, we present our numerical results concerning the synchronization properties of the closed-loop scheme. In correspondence with the experiments, two qualitatively different dynamical regimes are investigated, namely, the LFF, and the CC regimes. These two different situations are accessible by simply changing the current injection. In each of these regimes, we describe the dynamical behavior of the optical power of transmitter and receiver, as well as the corresponding degree of synchronization. In the absence of coupling, i.e., $\kappa_c = 0$, the dynamics of both lasers concerning power dropouts and subnanosecond pulsations is completely uncorrelated. There exists a critical value of the coupling, above which synchronization effects can be observed, for this particular case $\kappa_c \approx 15\ \mathrm{ns}^{-1}$. The important issue is that the correlation among the laser intensities is not only influenced by the coupling strength, but also strongly depends on the relative feedback phase. This fact is illustrated in Fig. 5 depicting the intensity time series of transmitter and receiver under LFF operation Fig. 5(a) and (b) and CC operation Fig. 5(c) and (d), respectively. Fig. 5(a) and (c) show that the intensity time series of the transmitter and receiver are highly correlated for adjusted feedback phase ($\Delta\Phi = 0$). This situation drastically changes in Fig. 5(b) and (d), where the two external cavities have a phase mismatch of $\Delta\Phi = \pi$, and a substantial drop in correlation is obtained. Under LFF operation, the receiver tends to follow the transmitter dynamics during the power recovering after a dropout, but as soon as it reaches high power levels, the receiver undergoes striking large-amplitude oscillations. This remarkable dynamical phenomenon is in good agreement with the experiment depicted in Fig. 2(a), which underlines the suitability of our rate equation model as a description of the complicated dynamical behavior of the system. A similar scenario occurs when the lasers operate far from the threshold current, i.e., well within the CC regime. In this case, power dropouts cannot be distinguished anymore, whereas the subnanosecond pulsations remain. Fig. 5(c) shows that these fast pulsations display a good correlation when $\Delta\Phi = 0$, while the correlation strongly decreases, as depicted in Fig. 5(d), when $\Delta\Phi$ is changed to π. Again, this is in good agreement with our experimental results, and further demonstrates the decisive importance of the relative feedback phase for the synchronization behavior of the system.

B. Synchronization Scenario for Variation of $\Delta\Phi$

As has been done for the experiments in Section II-B, we quantify the quality of the power synchronization through the cross-correlation coefficient defined in (1). Fig. 6 provides an overview on the optical-feedback phase-dependent synchronization scenario by plotting Σ_{corr} in dependence on $\Delta\Phi$, both for LFF operation Fig. 6(a) and CC operation Fig. 6(b) of the system. Different symbols correspond to different feedback rates of the receiver system. We observe a striking phenomenon when selecting parameters similar to the experimental conditions in Fig. 3, depicted with stars in Fig. 6, i.e., moderate coupling and receiver feedback strength lower than the transmitter. In qualitative agreement with the experiment, the correlation smoothly degrades when the relative phase is increased from zero, while there is a rapid increase when $\Delta\Phi > \pi$.

A possible interpretation of this phenomenon can now be given by analyzing the optical spectra of the transmitter and receiver systems. Since both solitary subsystems have different feedback strengths, their asymmetric optical spectra (due to the alpha-factor) do not completely overlap. The effect of the relative feedback phase can be regarded as an effective detuning, since it shifts the optical spectra of the receiver system when the coupling is present. Thus, the asymmetry in the correlation functions could arise from the asymmetry in the optical spectra, basically due to different overlap in the low- and high-frequency sides. Under CC operation depicted by the diamonds in Fig. 6(b), we numerically find that the maximum correlation for the optimal phase condition is obtained for moderate coupling conditions and when both subsystems have the same feedback rate. Furthermore, a small deviation from the optimal phase condition leads to a faster decrease in correlation. In the next section, we focus on this last situation and discuss its applications in chaotic carrier communications systems. Furthermore, we point out that our model has correctly reproduced the dynamics of the system over the whole range of $\Delta\Phi$. This underlines its validity with respect to the numerical test of the feasibility of the new ON/OFF phase shift keying to be presented in the following.

C. Communications: ON/OFF Phase Shift Keying

In the previous section, we have investigated the synchronization properties of the closed-loop scheme. We have confirmed the strong sensitivity of the synchronization behavior on $\Delta\Phi$ also observed in the experiment. This phenomenon suggests a novel encryption method based on the optical phase which we call ON/OFF phase shift keying. As already discussed, the fundamental idea consists in using the receiver system as a sensitive detector of the phase dynamics of the transmitter. In this subsection, we give first numerical evidence for the feasibility of this encoding scheme. A very important issue in encoded communication systems is the security of the scheme, and in a second place the maximum attainable transmission speed. The major drawback in the classical schemes based on amplitude modulation, such as chaos masking [8], [25], and chaos shift keying [1], is that the amplitude has to be kept small in order to avoid a direct recognition of the message. The enhanced privacy of the On/Off Phase Shift Keying stems from the phase nature of the keying: while the amplitude dynamics of the transmitter is almost unaffected, the receiver acts as a sensitive phase detector. Fig. 7 presents the calculated optical spectra of the transmitter, and the receiver operating in the CC regime while varying the transmitter feedback phase. Fig. 7(a) depicts the identical optical spectra in the synchronized state. Fig. 7(b) demonstrates that the optical spectrum of the transmitter remains unchanged for $\Delta\Phi = \pi$, while the optical spectrum of the receiver has drastically changed. Hence, the privacy of the proposed ON/OFF phase shift keying is quite high for the following reasons. First, it is unclear whether the detection of changes of the transmitter feedback phase is possible at all by observing the intensity time series only. Thus, an eventual eavesdropper cannot decide whether a message is sent or not. Second, the message recovery requires a careful control of the phases accrued within each external cavity laser. Finally, the high dimensionality of the chaos generated in the fully developed CC regime, illustrated in Fig. 7 by the large width of the optical spectra, i.e., $\approx$ 100 GHz, further enhances the confidentiality of the scheme. We numerically investigate the feasibility of the ON/OFF phase shift by varying the feedback phase of the transmitter through a train of pseudo-random bits. In order to to avoid

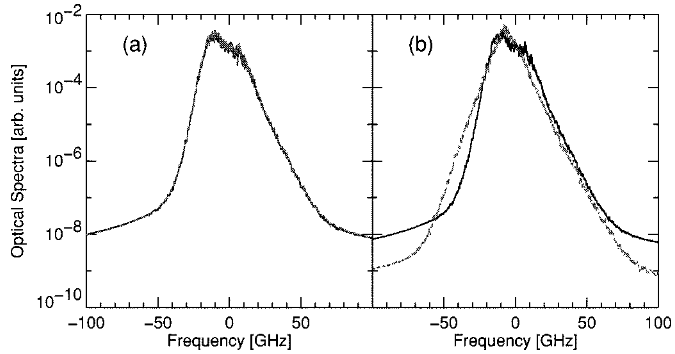

Fig. 7. Calculated optical spectra of the transmitter (black lines) and receiver (grey lines) when (a) $\Delta\Phi = 0$ and (b) $\Delta\Phi = \pi$. Parameters: $\kappa_r = \kappa_t = \kappa_c = 20\ \text{ns}^{-1}$, and $p_t = p_r = 1.5$.

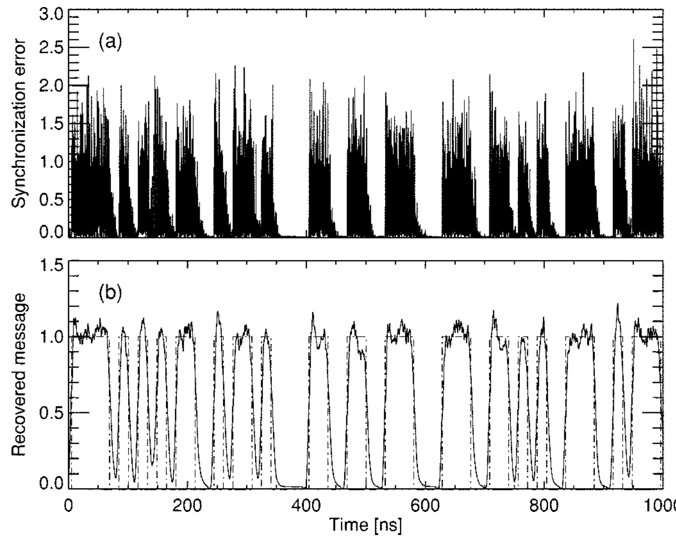

Fig. 8. ON/OFF phase shift keying encryption scheme. (a) Synchronization error defined in (7). (b) Recovered digital message at 64 Mb/s after a filtering process. Parameters: $\kappa_t = \kappa_r = 20\ \text{ns}^{-1}$, $\kappa_c = 30\ \text{ns}^{-1}$ and $p_t = p_r = 1.5$.

large excursions in the phase space, it is convenient to use small feedback phase variations. In simulations, we have changed the phase from an optimal value $\Phi_t = 0$ (Bit "0") to $\Phi_t = 0.16$ rad (Bit "1") where the correlation is already quite degraded. To evaluate the dynamical change in correlation, we compute the synchronization error that is defined through

$$\Lambda(t) = |\tilde{P}_r(t) - P_t(t)| \tag{7}$$

with $\tilde{P}_r(t) = (P_r - b)/m$ being the re-scaled receiver power. This scaling, that provides a relationship between transmitter and receiver intensity in a synchronized state, can be calculated using least squares method, obtaining $P_r = b + mP_t$, where b, m are fitting parameters. Using this rescaling, the comparison with the transmitter signal becomes straightforward. Fig. 8(a) depicts the synchronization error when a train of pseudo-random bits at 64 Mb/s is applied. Fig. 8(a) demonstrates that the synchronization error is almost zero when the two cavities are phase matched. On the other hand, the synchronization very rapidly degrades when the transmitter feedback phase is switched to $\Delta\Phi = 0.16$. Unfortunately, the inverse process, i.e., from the desynchronized state (bit 1) to the synchronized state (bit 0), is somewhat slower since a time interval of a certain minimum duration is required to recover the synchronization. This synchronization transient sets an upper limit for the data transmission rate. For our scheme, we are able to reach maximum bit rates of the order of 100 Mb/s, achieving reasonably open-eye diagrams. Fig. 8(b) demonstrates that the message can be recovered by applying a low-pass second-order Butterworth filter to the synchronization error, removing the high-frequency components. In our present investigations, the synchronization transients represent a limitation of the maximum achievable bit rate. Therefore, a comprehensive understanding of the synchronization process is necessary in order to reduce the transient times, and speed up the transmission. Notwithstanding, the restriction in speed is compensated by a substantial increase in privacy. The fact that the information is encoded in the phase of the electric field instead of the amplitude (as in the classical shift keying schemes) reduces the possibility of illegal decoding. Moreover, the correct message recovering also requires a careful adjustment of the feedback properties of the receiver that are, in turn, difficult to extract by an eavesdropper since the lasers operate well within the CC regime.

IV. Summary and Conclusions

To summarize, we have investigated synchronization phenomena in a closed-loop configuration consisting of two chaotically emitting semiconductor lasers subject to delayed optical feedback. The very similar subsystems have been unidirectionally coupled via their optical fields. We have demonstrated that the relative optical feedback phase is of decisive importance for the synchronization dynamics of the system: a characteristic synchronization scenario evolves under variation of the relative optical feedback phase which mediates cyclically between chaos synchronization and almost uncorrelated states. Based on these results, we have proposed, and given numerical evidence for a novel ON/OFF phase shift keying method. Future investigations will focus on the following two points. First, the new ON/OFF phase shift keying method has to be demonstrated experimentally. Second, the understanding of the mechanisms mediating between synchronization and uncorrelated states is of great relevance, e.g., in order to reduce synchronization transients which currently limit the maximum data transmission rates in the ON/OFF phase shift keying. In conclusion, our investigations have revealed several new perspectives of the closed-loop configuration for applications in communications systems using chaotic carriers. In comparison with the latter, it is obvious that the open-loop configuration is simpler and, therefore, more robust. However, our results also shows that the more complex closed-loop configuration exhibits clear advantages. A key feature is the ON/OFF phase shift keying method proposed in this paper, which is a peculiarity of the closed-loop configuration. This new method exhibits a great potential for enhanced privacy data transmission applications, because the detection of transmitter phase variations from a transmitter time series alone is at least very difficult, whereas the reconstruction of the data using an appropriately operated receiver is a straightforward process. Finally, we note that the availability of a suitable rate equation model is an advantage in all configurations applying chaotic SLs in communication systems using chaotic carriers.

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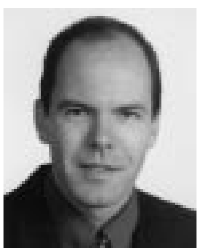

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