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Synchronization of chaotic semiconductor laser dynamics on subnanosecond time scales and its potential for chaos communication

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We present experimental evidence for the synchronization of two semiconductor lasers exhibiting chaotic emission on subnanosecond time scales. The transmitter system consists of a semiconductor laser with weak to moderate coherent optical feedback and therefore exhibits chaotic oscillations. The receiver system is realized by a solitary semiconductor laser in which a fraction of the transmitter signal is coherently injected. We find that for a considerably large parameter range, synchronized receiver output can be achieved. We discuss the physical mechanism and demonstrate that the receiver acts as a chaos pass filter, which reproduces the chaotic fluctuations of the transmitter laser, but suppresses additionally encoded signals. Signal extraction at frequencies of up to 1 GHz has been achieved. Thus we provide a simple and robust optical chaos synchronization system that is promising for the realization of communication by sending signals with chaotic carriers.

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The possibility of the synchronization of chaotic oscillators by suitable coupling is a fascinating phenomenon that attracts interest in many fields of science, e.g., in biological [1] or optical systems [2]. The idea of taking advantage of this phenomenon for chaotic communication [3] has found considerable interest in recent years because of its high potential for spread spectrum communication with inherent chaotic encryption. From this point of view, optical systems and in particular semiconductor lasers, being the standard devices used in optical communication technology, are regarded as having a high potential. The first successful realizations based on a fiber laser system [4] and on semiconductor laser systems with external nonlinearity [5] have been reported. We concentrate on a semiconductor laser system with optical feedback to take advantage of the inherent nonlinearities of the semiconductor laser. This system has been intensively studied, both theoretically and experimentally, and it has been experimentally demonstrated that the relevant time scales for the chaotic dynamics can lie far into the GHz range [6], opening the perspective for potentially high transmission rates. Several numerical investigations have obtained promising results for the possibility of realizing synchronization [7,8]. In the first experimental studies, synchronized irregular fluctuations on microsecond-millisecond time scales were found [9]. In this Rapid Communication we demonstrate chaos synchronization down to subnanosecond time scales and even signal encoding and decoding at a frequency of up to 1 GHz.

We have performed the experiments using two Anritsu SD3F513T semiconductor lasers emitting at about 1460 nm. These lasers allow for output powers up to 120 mW at injection currents of 300 mA. They emit multilongitudinal mode and single lateral mode up to 80 mA. These lasers have been chosen because they exhibit nearly equal threshold currents around 24 mA and similar slopes of the L/I characteristics. The differences are of the order of 3%, respectively. Also, the emission wavelengths of these lasers coincide within a few nanometers. However, since the emission is multimode, the exact spectral features may be distinctly different. The lasers are driven by low-noise current sources and temperatures stabilized with 0.01 K accuracy. The scheme that we have used in order to realize synchronized dynamical output of two semiconductor lasers is depicted in Fig. 1. It is a so-called ''open-loop scheme.'' The emission of the first laser, called the transmitter in the following, is collimated by a microlens. An external cavity is realized by a high reflecting gold mirror. The round-trip time of the light in the external cavity amounts to $\tau = 3.6$ ns. The amount of feedback can be varied by a variable neutral density filter. About half of the emitted intensity is coupled out of the external cavity and coupled into a single-mode fiber. In order to avoid unwanted reflections from the fiber back into the transmitter laser, an optical isolator with 45-dB isolation has been introduced. Another variable neutral density filter is used to vary the amount of injection into the second laser, called the receiver

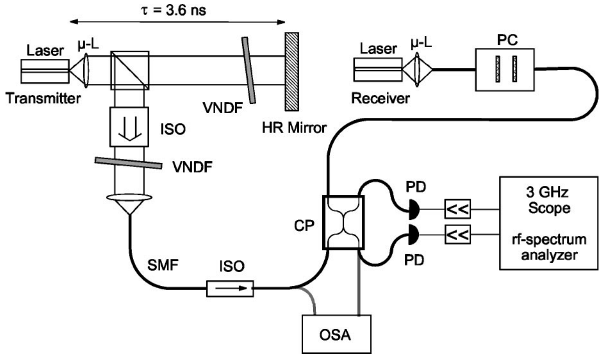

FIG. 1. Experimental setup; μ-L, microlens; VNDT, variable neutral density filter; ISO, optical isolator; SMF, single-mode fiber; CP, 70:30 fiber coupler; PD, 6 GHz photodiodes; PC, polarization controller; OSA, optical spectrum analyzer.

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in the following. The receiver system does not contain an external cavity. In the fiber transmission line another optical isolator with 25 dB has been introduced so that unidirectional coupling from the transmitter to the receiver can be maintained under all conditions. The transmitted light is divided by a 70:30 fiber coupler. The two strong ports have been used to connect the transmitter to the receiver to allow for high injection levels. The weak output is directed toward a 6-GHz photodiode (New Focus 1514-LF) to detect the dynamical behavior of the transmitter. The strong output is coherently injected into the receiver by a microlens. In order to compensate for the polarization distortions in the fiber transmission, a polarization controller has been inserted before coupling the light into the receiver. From the fourth port of the fiber coupler the dynamical behavior of the receiver laser can be detected by means of another 6-GHz photodiode. The signals from the two photodiodes are amplified by two dc 6-GHz amplifiers and can be monitored simultaneously with a 3-GHz bandwidth and 10 G samples per second by a fast digitizing oscilloscope (Tektronix TDS 694 C), or analyzed by a rf spectrum analyzer with a 22-GHz bandwidth (Hewlett-Packard 8566 B). The optical spectra of the two lasers have been analyzed by means of an optical spectrum analyzer (Hewlett-Packard 70950 A) with a resolution of 0.1 nm, which is sufficient to resolve the longitudinal modes of the semiconductor lasers.

We apply weak to moderate coherent optical feedback to the transmitter laser. In the weak feedback regime, the laser shows destabilized relaxation oscillations. We drive the laser at injection currents between 24 and 57 mA in order to maintain lateral single mode behavior and to keep the relaxation oscillation frequency below 3 GHz, which is the bandwidth of our temporal detection. In the moderate feedback regime, we find in the same current range the typical low-frequency fluctuations (LFF) at low currents and also the fully developed coherence collapse at higher currents. For each of these chaotic regimes we are able to realize synchronized chaotic output of the transmitter and the receiver. However, in the following we restrict ourselves to the description of the weak feedback case. In order to achieve synchronized output we have to adjust several experimental parameters. First, we tune the wavelength of the receiver laser to roughly coincide with the transmitter laser by temperature variation. We also have to compensate for the polarization rotation and birefringence due to the fiber transmission, which is done by means of the polarization controller. When injecting the light from the transmitter coherently into the receiver, we can achieve a complete reproduction of the transmitter's optical spectrum in the receiver. We identify this as an injection locking phenomenon. The injection locking for the chaotic case can be maintained for a spectral width of about 1.5 nm when tuning the receiver via temperature. Figure 2 shows the optical spectra of transmitter and receiver under these injection locking conditions. They correspond very well to each other and only tiny differences may be identified. In order to obtain the best correlation of the dynamics of the transmitter and the receiver emissions, we have to adjust the amount of optical injection and the injection currents of the transmitter and the receiver. In Fig. 3, we depict two time series obtained under optimized conditions. The optical injection corresponds to 5–10 % of the transmitter's output power and to 23% of the solitary receiver's power. The figure shows two traces for the transmitter laser and the receiver laser, respectively. They have been shifted in the vertical direction for clarity. The temporal length of the traces has been chosen to be 10 ns. Therefore the relaxation oscillations at a frequency of about 2.5 GHz exhibiting irregular amplitude modulation can be clearly recognized. We would like to emphasize that the chaotic emission of a semiconductor laser with weak optical feedback can be sufficiently resolved, including the relaxation oscillations, to allow for the characterization of the dynamical behavior based on experimental time series and thus a review of the scenario. We have applied a false nearest-neighbor algorithm and correlation dimension methods to the time series in order to verify that the observed behavior is not low dimensional. As expected in this regime, the dynamical behavior exhibits chaotic emission with more than seven dynamical degrees of freedom [10]. The two time series of the transmitter and the receiver coincide very well, giving evidence for the possibility of achieving synchronized output from two semiconductor lasers emitting chaotically due to optical feedback. To visualize the degree of synchronization, we plot in Fig. 4 the emitted intensities of the transmitter and the receiver against each other, coding the density of data points by colors. The coding ranges from red, which represents high density, to yellow and green to blue, which

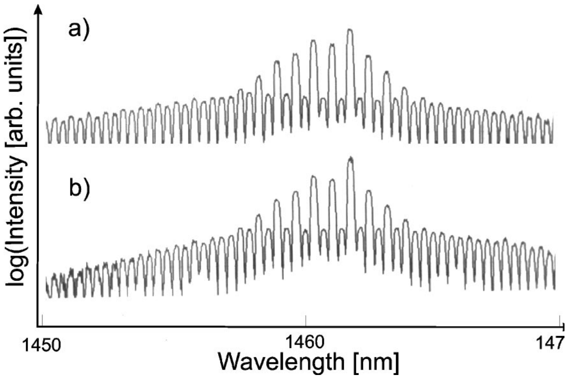

FIG. 2. Optical spectra of (a) transmitter and (b) receiver laser in the injection locking range.

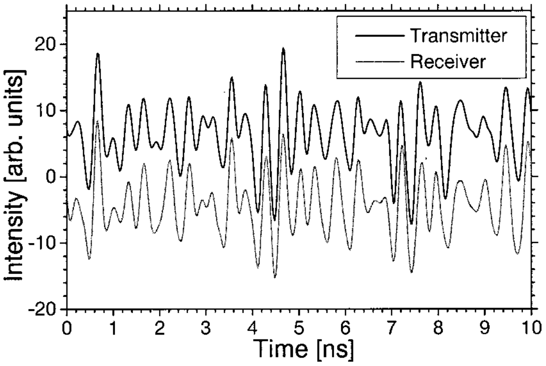

FIG. 3. Synchronized output intensity time series of transmitter (upper trace) and receiver lasers (lower trace).

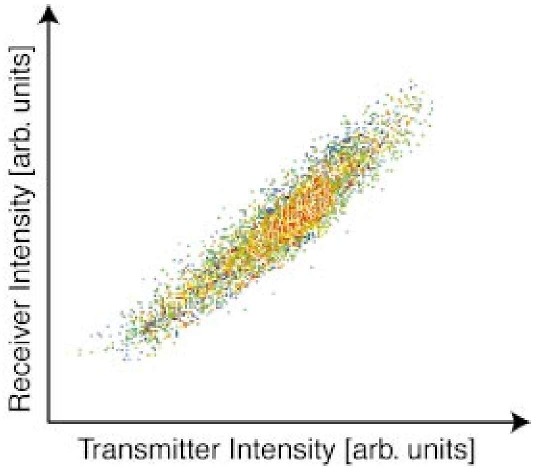

FIG. 4. (Color) Correlation plot of transmitter and receiver intensity. The density of points is color coded ranging from red for high density via yellow and green to blue for low density.

represents low density. This plot is based on a long-time average that considers many time series obtained over 500 ms. It can be recognized that the unstable relaxation oscillations occur around a mean intensity value as expected. Furthermore, the strong correlation of the transmitter and receiver output can be clearly recognized from the density distribution being mainly restricted to the diagonal.

Based on these results, we have tried to verify how far this observed behavior corresponds to chaos synchronization, as predicted in numerical modeling, e.g., by Ahlers *et al.* [8], which, however, does not consider any detuning of the two lasers. For this kind of chaos synchronization, the emitted signal from the transmitter laser can be regarded as the driving signal for the chaotic oscillations of both the transmitter and the receiver lasers. Therefore the time lag of the synchronized output from the transmitter and the receiver, $\tau_{t,r}$, is expected to be $\tau_{t,r}=\tau_c-\tau$, with τ denoting the delay time of the light in the external cavity and τ_c the propagation time of the coupling signal from the transmitter to the receiver. Thus $\tau_{t,r}$ should vary when changing τ. However, this is not what we observed in our experiments. From both the latter observation and an estimation of τ_c, we conclude that the time lag between transmitter and receiver is given by $\tau_{t,r}=\tau_c$. Furthermore, the parameter range in which synchronization can be achieved is significantly larger compared to the predictions from the modeling. The temperature of the receiver laser can be varied by more than 2 K, corresponding to an average detuning of the free-running emission wavelength of ~1.5 nm, and the injected power can be varied between 4% and 35% of the solitary receiver's power without losing synchronized output. We would like to point out that these phenomena have not been predicted by theory and numerical modeling yet. Therefore we have to clarify how this observed behavior can be understood in terms of synchronization phenomena. The time lag might suggest that what we observe is only an amplification of the transmitter emission. However, the receiver laser is always driven above laser threshold. Since the observation of synchronized emission is related to the observation of coinciding optical multimode spectra, we interpret the phenomenon to be closely related to injection locking of the receiver laser to the transmitter laser. The main questions in this context regard how the matching of optical spectra, interpreted as injection locking, and the similarity of the intensity dynamics, referred to as synchronized output, relate to each other; in particular:

(i) Does matching of the optical spectra of transmitter and receiver, when injecting a chaotic signal, imply synchronized chaotic output?

(ii) Does our configuration exhibit any chaos pass filtering properties; i.e., is the receiver capable of separating the chaotic fluctuations from any other superimposed fluctuations?

In order to answer the first question, we have tuned the temperature and thus the wavelength of the receiver laser and observed optical spectra and transmitter/receiver correlation plots. In our experiment, only a slight influence of the degree of synchronization on the receiver wavelength can be observed when inside the complete injection locking regime. When approaching the edges of this regime, intermittent breakdowns of the synchronization can be observed. These desynchronizing events are related to one or several additional longitudinal modes coming up in the optical spectrum of the receiver. Thus we find, at least under the conditions covered in our experiments, that there is a close correspondence between the breakdown of injection locking and the breakdown of the observation of synchronized output. Therefore the observation of the optical spectrum provides a very simple and efficient means to determine whether the receiver exhibits synchronized emission or not. However, knowing about the unstable and chaotic regimes in the cw-injection locking case, depending on the detuning, as has been intensively studied (see, e.g., [11]), this question needs some further clarification in detailed future experiments. From the point of view of the fundamental properties of the synchronized emission and also from the applications point of view, the second question is the key question. It is necessary to test whether or not the observed synchronized behavior is due to linear amplification. We have to clarify that we are able to distinguish an injected chaotic signal from an additional signal modulation that is in the same frequency range as the chaotic carrier. This is what we define to be a ''chaos pass filter.'' The observation of synchronized chaotic emission and the test for these chaos pass filter properties is what we, from an experimentalist's point of view, define as chaos synchronization. Therefore we have performed experiments additionally applying a sinusoidal modulation to the injection current of the transmitter laser. The amplitude of the modulation can be chosen to be comparatively small, so that except for at the modulation frequency, the rf spectrum of the chaotic emission is not affected or only slightly altered by the modulation. Figure 5(a) shows the rf spectrum of the transmitter laser with a current modulation at a frequency of 581.5 MHz. For better clarity, we have chosen a somewhat higher modulation amplitude. This spectrum is typical for feedback-induced chaos. The broad maxima of the spectrum correspond to the round-trip frequency of the light in the external cavity at $f_{fb}=275$ MHz and harmonics of it. The sharp peak corresponds to the frequency of the external current modulation. Figure 5(b) depicts the corresponding rf

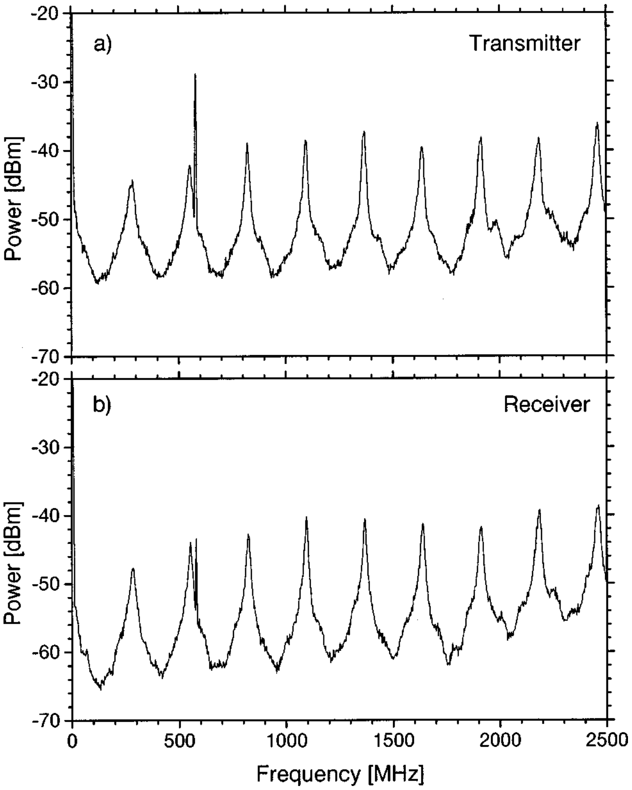

FIG. 5. rf spectra of (a) transmitter and (b) receiver laser in the synchronization regime. The injection current of the transmitter laser has been modulated at a frequency of $f_{mod}=581.5$ MHz.

spectrum of the receiver laser. The main features of the chaotic spectrum are very well reproduced in the receiver and correspond nicely to those of the transmitter output. However, the external modulation peak is found to be considerably weaker in the receiver output compared to the transmitter output. At some frequencies the amplitude of the modulation of the transmitter's emission, caused by the external modulation, can become even larger than the amplitude of the chaotic fluctuations, but still the receiver laser mainly recovers the fluctuations related to the chaotic dynamics and only to a much smaller extent the external modulation features. It is obvious from these observations that the modulation signal can be easily recovered by normalizing the transmitter and receiver signals and subtracting them from one another. We have proven this in the experiment in the frequency range from 20 MHz to 1 GHz and we could achieve signal extraction up to 1 GHz, which is what we believe the highest frequency yet reported for signal transmission with chaotic carriers. The modulation amplitude was still low enough to guarantee that the intensity modulation of the transmitter introduced by this current modulation was significantly smaller than the amplitude of the chaotic oscillations. Therefore when using a real data modulation scheme, rather than just sinusoidal modulation, as used here, chaotic masking by this inherent encoding method appears possible.

In conclusion, we have presented experimental evidence for the chaos synchronization of two semiconductor lasers on subnanosecond time scales for multilongitudinal mode emission. We would like to point out that related results, also demonstrating the synchronized output of two semiconductor lasers showing delayed feedback instabilities on nanosecond time scales, have been obtained independently by Fujino *et al.* [12]. The parameter range in which we achieve chaos synchronization is distinctly larger when compared to the predictions of previous model calculations of this type of system. We interpret this difference and the different time lag between the transmitter and the receiver to be caused by injection locking phenomena in the receiver laser. The enlarged range for synchronization makes this configuration even more attractive, because it opens the perspective for achieving chaos synchronization even under ''real world'' conditions in applications. Finally, we have proven that our scheme allows for signal coding and decoding up to at least 1 GHz, based on the chaos pass filtering performed by the receiver.

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[1] A.M. Sillito, H.E. Jones, G.L. Gerstein, and D.C. West, Nature (London) **369**, 479 (1994); C.M. Gray, P. Konig, A.K. Engel, and W. Singer, *ibid.* **338**, 334 (1989).
[2] T. Sugawara, M. Tachikawa, T. Tsukamoto, and T. Shimizu, Phys. Rev. Lett. **72**, 3502 (1994); R. Roy and S. Thornburg, *ibid.* **72**, 2009 (1994).
[3] L.M. Pecora and T.L. Carroll, Phys. Rev. Lett. **64**, 821 (1990).
[4] G.D. Van Wiggeren and R. Roy, Science **279**, 1198 (1998).
[5] J.P. Goedgebuer, L. Larger, and H. Porte, Phys. Rev. Lett. **80**, 2249 (1998); Y. Liu and P. Davis, Opt. Lett. **25**, 475 (2000).
[6] I. Fischer *et al.*, Phys. Rev. Lett. **76**, 220 (1996); T. Heil, I. Fischer, and W. Elsäßer, Phys. Rev. A **60**, 634 (1999).
[7] C.R. Mirasso, P. Colet, and P. Garcia-Fernandez, IEEE Photonics Technol. Lett. **8**, 299 (1996); V. Annovazzi-Lodi, S. Donati, and A. Scire, IEEE J. Quantum Electron. **33**, 1449 (1997); J.K. White and J.V. Moloney, Phys. Rev. A **59**, 2422 (1999).
[8] V. Ahlers, U. Parlitz, and W. Lauterborn, Phys. Rev. E **58**, 7208 (1998).
[9] S. Sivaprakasam and K. Shore, Opt. Lett. **24**, 466 (1999).
[10] R. Hegger, H. Kantz, and T. Schreiber, Chaos **9**, 413 (1999).
[11] T.B. Simpson *et al.*, Appl. Phys. Lett. **64**, 3539 (1994).
[12] H. Fujino and J. Ohtsubo (unpublished).