1.5-GHz message transmission based on synchronization of chaos in semiconductor lasers

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Sinusoidal message transmission up to 1.5 GHz is performed based on synchronization of chaos in experimental nonlinear systems of semiconductor lasers with optical feedback. In the chaotic systems the message is almost entirely suppressed in the receiver output, even if the message has nonnegligible power in the transmitter. © 2002 Optical Society of America

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Synchronization of chaotic oscillations in coupled nonlinear systems is an important issue in chaos research. Since the prediction of synchronization of chaos by Pecora and Carroll, synchronization of chaotic oscillations between two nonlinear systems has been reported in various fields of engineering. In optics, experimental synchronization between two chaotic laser systems has also been demonstrated in solid-state lasers and in CO₂ lasers. Also, there have been many theoretical studies of the synchronization of chaotic oscillations in semiconductor laser systems. Recently, experimental synchronization in semiconductor lasers was also reported. Most experimental attempts to synchronize chaos were based on optical injection-locking phenomena in a master–slave configuration of transmitter and receiver lasers, which is also called generalized chaos synchronization. A few experiments were directed toward the complete synchronization of chaos, in which the rate equations for both the master and the slave lasers can be written by the same or equivalent differential equations.

Synchronization of chaotic lasers is important for practical applications in optically secure communications. Chaos is dependent on hardware, and it is not easy to analyze chaotic signals without knowing the chaos keys. Therefore we can construct secure communicating systems. In secure communications based on chaos synchronization, a message together with a chaotic carrier is sent to a receiver. In the receiver system, only the chaotic carrier from the transmitter is duplicated by chaos synchronization, and thus the message can easily be decoded. In semiconductor laser systems, chaotic secure communications have been investigated theoretically, and the experimental verifications were recently reported. We can use either a complete or a general synchronization scheme for chaos communications, though the robustness of the communication seems to be different in each case. Gigahertz synchronization of chaotic oscillations in semiconductor lasers with optical feedback and the possibility of high-bit-rate data transmission have already been discussed.

In this Letter we describe a chaos generator that comprises a semiconductor laser with optical feedback. With a master–slave laser configuration, synchronization of chaotic oscillations of the order of gigahertz is performed. The synchronization is based on the optical injection–locking phenomenon, the so-called generalized chaos synchronization. A sinusoidal signal with a frequency as high as 1.5 GHz is encoded into chaotic carriers in the transmitter as a message, and decoding is done simply by subtraction of the synchronized chaotic output of the receiver from the transmitted signal. A successful reconstruction of the message by the chaos masking technique is demonstrated. We also discuss the degrees of signal reconstruction through a narrow-bandpass filter centered at the frequency of the transmitted message. The experimental setup was almost the same as that described previously. The transmitter consisted of a semiconductor laser with optical feedback, and the receiver was a solitary laser. The distance between the external mirror and the laser facet in the transmitter system was 35 cm. Under these conditions synchronization of chaotic oscillations was realized by appropriate injection of the light from the transmitter into the receiver laser. The semiconductor lasers used were intrinsically single-mode InGaAlAs V-channeled substrate inner-stripe lasers (Sharp LT024MD) that oscillated at a wavelength of 780 nm and had a maximum power of 30 mW. The free-running threshold currents of the master and the slave lasers were 46.0 mA at 25.4 °C and 43.6 mA at 24.5 °C, respectively. The injection currents for the master and the slave lasers were biased at 69.0 mA (1.50 Iₜh, where Iₜ is the laser threshold current) and 68.0 mA (1.56 Iₜh), respectively, at the same temperatures. The feedback fraction from the external mirror to the laser cavity in the transmitter was 3.75% of the intensity fluctuations of chaotic oscillations. Note that this amount was not exactly equal to the actual feedback power of the internal laser cavity because of losses in the optical components and diffraction of the collimating lens. The optical injection from the master to the slave lasers was 6.45%. The frequency detuning between the two lasers was measured at 3.1 GHz during the lasers’ free-running states. The laser output from the transmitter was spatially sent to the receiver, and the distance between the transmitter...
and the receiver lasers was ~80 cm. The relaxation oscillation frequencies for the master and the slave lasers were almost equal at 4.1 GHz for free-running bias injection current with the values given above. With optical feedback, the relaxation oscillation frequency of the transmitter laser increased to 4.4 GHz.

A sinusoidal signal of a frequency up to 1.5 GHz was used as a message, and the injection current of the transmitter laser was directly modulated by the signal. We have examined chaotic data transmissions at several frequencies. Figure 1 shows an example of synchronized chaotic waveforms of transmitter and receiver outputs in the presence of a message with 1.5-GHz modulation. In actuality there was a time lag between the two observed laser outputs; however, the time lag has been compensated for in the figure to show the degree of synchronization. Because the modulation was degraded owing to the finite time response of the injection modulation circuit (bandwidth of 1.7 GHz) and other signal transmission losses, it was not easy to measure the exact modulation depth for the injection current. The net depth of the modulation for the injection current was estimated to be ~1 mA. In Fig. 1 the upper trace is the time series of the transmitter and the lower trace is that of the receiver. We can see synchronized waveforms of the transmitter and receiver outputs in Fig. 1. Note that these traces correspond to the synchronization of chaotic oscillation generated by the optical injection-locking phenomena previously referred to as generalized synchronization of chaos. Although it is not shown here, the correlation plot between the transmitter and the receiver outputs showed a linear relation and supported the synchronization, even in the presence of modulation of the message in the transmitter output.

Figure 2 shows optical spectra that correspond to those of Fig. 1. Figure 2(a) is the spectrum of the transmitter output. Besides the broad spectral peaks of the external cavity mode and its higher harmonics, a sharp spectral peak with the message of 1.5 GHz can clearly be seen in the spectrum. The spectrum of the receiver output does not show any distinct spectral peak to correspond to the message, as we show in Fig. 2(b). However, the overall structure of the spectrum of the receiver output well resembles that of the transmitter, except for the message component. It is notable that in chaotic data communications a message signal is highly suppressed in the receiver even if a message has a nonnegligible power at less than a certain level. This is always true for both complete and generalized synchronization of chaos. The suppression of the message component in the receiver system has been discussed in numerical simulations and verified by experiment. However, a reasonable explanation for it has not been given.

Figure 3 shows the recovered message obtained by subtraction of the receiver output from the transmitter output in Fig. 1. The upper trace (solid curve) in Fig. 3 is the reconstructed 1.5-GHz waveform of the message signal with a low-pass filter of 2-GHz bandwidth. The waveform was almost the same as the waveform without the filter (simply the subtraction of one waveform from the other in Fig. 1), because the digital oscilloscope used for signal observations had a limitation of a bandwidth of 1.5 GHz. The middle (dotted curve) is the low-pass filtered waveform of the transmitter with the same bandwidth of 2 GHz. The bottom trace (dashed curve) is also the low-pass filtered waveform for the receiver. The message at the frequency of 1.5 GHz was well reconstructed, as shown in the figure. The filtered waveforms for the transmitter and the receiver lasers also seem to oscillate at a frequency of 1.5 GHz. However, these oscillations have been proved to be pseudoperiodic oscillations and are slightly unequal to the message waveform including the phase. Figure 4 shows narrow-bandpass filtered waveforms with ±100-MHz bandwidth centered at the message frequency for the decoded message (upper) and for the transmitter (middle) and the receiver outputs.
We have demonstrated message transmissions of a sinusoidal waveform up to 1.5 GHz based on synchronization of chaos in semiconductor lasers with optical feedback. The synchronization was categorized into a generalized synchronization scheme of chaotic oscillations that originated from optical injection locking in semiconductor lasers. Only the chaotic carrier has been duplicated in the receiver system, and the message has been successfully reconstructed by subtraction of the chaotic oscillation of the receiver from the transmitted signal. We have demonstrated that the recovered message was quite different from the narrow-bandpass filtered waveforms of the transmitter and the synchronized receiver outputs. Thus we can securely transmit a message with a high data bit rate in synchronized chaos. However, the degree of security in chaotic data transmission still remains an important problem for future study.

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