Experimental synchronization of chaotic oscillations in external-cavity semiconductor lasers

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Synchronization of fast chaotic oscillations of the order of gigahertz is experimentally observed in two external-cavity semiconductor lasers. © 2000 Optical Society of America

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Over the past two decades a considerable number of studies have been conducted on the dynamics of semiconductor lasers with optical feedback, because a wealth of chaotic phenomena can be found in these nonlinear laser systems.1 One of the important phenomena is synchronization of chaotic oscillations between two laser systems. Recently, synchronization of chaotic systems has been of interest from the viewpoint of secure communications. In secure communication systems based on chaos, a message is encoded within a chaotic carrier in a transmitter and transmitted to a receiver. In the receiver system, only the chaotic carrier is duplicated by chaos synchronization, and the message can be easily decoded.

Synchronization of chaotic lasers is a key to such optical secure communication systems. Experimental synchronization between chaotic laser systems has already been demonstrated in solid-state lasers2–8 and CO2 lasers.4 Chaotic optical secure communication systems have also been proposed in several laser systems.3,6 Little experimental study of synchronization of chaotic oscillations in semiconductor lasers has been conducted,7,8 although there exist a number of numerical simulations.9,10 An external-cavity semiconductor laser is a potential device for a secure optical communication system, since it is easy to obtain chaotic output and a very compact chaotic device can be achieved.

In this Letter we experimentally demonstrate synchronization of chaotic oscillations in two external-cavity semiconductor lasers on the nanosecond time scale. Synchronization between two external-cavity semiconductor lasers has already been reported, but previous results of synchronization of chaotic oscillations were for the low-frequency range (less than several megahertz)1 and for low-frequency fluctuation regimes.8 In general, three types of synchronization scheme can be considered for chaotic external-cavity semiconductor laser systems.8 Two types of system were used in our synchronization experiments. The first is an injection system in which the transmitter is an external-cavity semiconductor laser and the receiver is a solitary semiconductor laser. In the second system the transmitter and the receiver are similar external-cavity semiconductor lasers. In these systems the injection directions are unidirectional, and they form a master–slave configuration. The first system is considered to be a special case of the second one. That is, the second system reduces to the first when the external mirror in the receiver system is removed or, equivalently, its reflectivity is set to be zero. For both systems chaotic outputs from the lasers can be synchronized in the appropriate parameter conditions. In this Letter, synchronization of chaotic oscillations on the nanosecond time scale is investigated.

The experimental setup is shown in Fig. 1. The semiconductor lasers used in our experiments were intrinsically single-mode AlGaInP multiple-quantum-well diode lasers (Mitsubishi ML1412R) that oscillated at a wavelength of 690 nm and a maximum power of 30 mW. The master laser (ML) together with mirror M1 forms a chaotic transmitter, and the slave laser (SL) together with mirror M2 is a receiver in the chaotic synchronization system. The free-running threshold currents of the master and the slave lasers were 27.0 and 27.1 mA, respectively. The bias injection currents of the master and the slave lasers were controlled by stabilized current-source drivers. The temperatures of the master and the slave lasers were stabilized at 25.0 and 24.5 °C, respectively, by automatic temperature control circuits. At and near those temperatures, no internal mode hopping originating from temperature fluctuations was observed. The two lasers used in our experiment have very similar oscillation frequencies and slope efficiencies. The relaxation-oscillation frequencies of the two lasers were

Fig. 1. Experimental setup for synchronization of chaotic external-cavity semiconductor lasers. BS1–BS3, beam splitters; OI, optical isolator; PL, polarizer.

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almost the same, \( \sim 1 \) GHz at the thresholds. The external-cavity lengths were chosen to be 29 cm in both cases. The external reflectivities of the master and the slave lasers were changed by neutral-density filters NDF1 and NDF2, respectively. The coupling strength from the master laser to the slave laser was changed by rotation of a \( \lambda/2 \) wave plate with a fixed polarizer. At a certain bias injection current and a moderate optical feedback level, the output power from the master laser showed chaotic oscillation and was injected into the slave-laser cavity through an optical isolator with an isolation ratio of 40 dB. The feedback level and the coupling strength were calculated in the external optical system, and the real fractions of the feedback and the injection into the internal laser cavity were different from these values owing to the diffraction effect of a collimating lens and other losses of light. The actual levels of the feedback and injection fractions were roughly estimated to be one tenth of the values. In the experiment we fine tuned the feedback level and the coupling strength to obtain the best synchronization.

The output intensities of both the master and the slave laser were detected by high-speed photodetectors PD1 and PD2, respectively (New Focus 1537M-LF; bandwidth, 6.0 GHz), and the detected signals were amplified by amplifiers AMP1 and AMP2, respectively (New Focus 1421; bandwidth, 20 GHz). The chaotic waveforms were analyzed by a rf spectrum analyzer (Hewlett-Packard 8595E; bandwidth, 6.5 GHz) and a fast digital oscilloscope (Hewlett-Packard 54845A; bandwidth, 1.5 GHz). For synchronization by injection (i.e., in the case of the first synchronization system mentioned above), the injection fraction to the slave laser was set to be almost equal to the feedback fraction in the master laser. For the second synchronization system, the total feedback and injection fractions in the slave laser were almost equal to the amount of feedback into the master-laser cavity. In both cases synchronization of chaotic oscillations on the nanosecond time scale was observed.

Next we show the results for the second synchronization scheme discussed above. Figure 2 shows the chaotic waveforms and the correlation plot. We tried to find the parameter regions for the best synchronization of chaotic oscillations in the two external-cavity semiconductor lasers by changing the parameter values. Figure 2 shows the resulting chaotic waveforms for injection currents of 33.0 mA for the master laser and 31.8 mA for the slave laser. The coupling fraction from the master laser to the slave laser (which is calculated in the external system and is not an exact fraction into the laser cavity) was \( \sim 4.6\% \) of the slave-laser output power. The optical feedback fractions in the master- and the slave-laser systems were approximately 0.93\% and 0.48\%, respectively. At this feedback level the slave laser showed chaotic oscillation without injection from the master laser. The chaotic waveform of the slave laser after synchronization is quite similar to that of the master laser, and a linear relation between the two lasers is well established. This result clearly shows that the chaotic oscillations in the two external-cavity semiconductor lasers were synchronized on the nanosecond time scale. As shown in Fig. 3, the rf spectra of the master- and the slave-laser outputs are almost identical in this state, which also supports the synchronization between the two systems. In the same way similar results were obtained for the first synchronization system; however, as for the parameter mismatch, the synchronization range of the second system seems to be rather robust compared with that of the first one.

We have experimentally demonstrated synchronization of chaotic oscillations in two external-cavity semiconductor lasers of the order of gigahertz. According to Ref. 10, chaos synchronization in a mathematical sense is realized in external-cavity semiconductor laser systems with a time delay of \( \Delta t = \tau_c - \tau \), in which the two systems can be described by exactly the same differential equations, where \( \tau_c \) is the transmission time of light from the master laser to the slave laser and \( \tau \) is the round-trip time in the feedback loop. In our experiments the observed time of the delay between the two lasers’ outputs was only \( \tau_c \), the time delay between the two waveforms in Fig. 2 was

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![Fig. 2](image_url)

**Fig. 2.** (a) Synchronized chaotic waveforms for the master laser and the slave laser. (b) Correlation plot of the outputs from the master and the slave lasers.

![Fig. 3](image_url)

**Fig. 3.** Rf spectra of (a) the master-laser and (b) the slave-laser outputs corresponding to those in Fig. 2.
compensated for), and delay depending on $\tau$ was not observed. The dependence of the delay time on only $\tau_c$ follows from the fact that the result of our experiment is not a chaos synchronization in the mathematical sense. However, synchronization of chaotic oscillations in our case is somewhat different from the usual injection or amplification phenomena in semiconductor lasers, since two laser outputs can be synchronized with a small amount of injection even if, without the injection, the two lasers oscillate chaotically in an independent manner and the coherence of the lasers is completely destroyed under chaotic oscillations. This synchronization of chaos can be called generalized synchronization and is distinguished from complete synchronization of chaos in the mathematical sense. A discussion of the difference between complete and generalized chaos synchronization can be found in Ref. 11.

The method of secure communications that has been proposed here is based on complete synchronization of chaos. However, secure communications can be realized whether the synchronization comes from complete or generalized synchronization of chaos, since only the chaotic waveform is well reproduced in the receiver output even if a message is embedded into the chaotic carrier. In future studies the experimental demonstration of complete chaos synchronization in our system is expected. Investigation of the difference of the phenomena of complete and generalized chaos synchronization is an interesting issue, and the robustness of the synchronization for the parameter mismatch is another important problem.

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