Experimental Demonstration of Anticipating Synchronization in Chaotic Semiconductor Lasers with Optical Feedback

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We report the first experimental observation of anticipating chaotic synchronization in an optical system using two diode lasers as transmitter and receiver. The transmitter laser is rendered chaotic by application of an optical feedback in an external-cavity configuration. It is found that the anticipation time does not depend on the external-cavity round trip time of the transmitter.

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Synchronization of chaotic nonlinear systems has been given much attention in the recent past due to its potential in various applications, especially in secure communications [1–9]. The basic concept of such work is to synchronize two chaotic systems so as to enable efficient transmission and reception of messages. Communicating a message was demonstrated using a chaotic fiber laser [10] and using a novel form of wavelength chaos in semiconductor lasers [11]. Synchronization of chaotic semiconductor laser diodes is of special interest due to their ease of operation in high-speed optical communications and due to their potential in secure communications. Synchronization of chaotic diode lasers [12] and message encoding and decoding [13,14] have been demonstrated recently. Encoding and effective decoding of a message depend critically on the quality of synchronization between the two chaotic lasers used as transmitter and receiver.

Experiments on message transmission using fiber lasers and diode lasers have shown that the recovery of message critically depends on taking into account the time delay arising due to a time lag in the receiver dynamics [10,13]. This time lag, known as the retardation time (τ_C), primarily arises due to the time taken for the light to travel from the transmitter to the receiver. All previous experimental work [10–14] therefore has been concerned with *lag synchronization.* Recently, Voss [15] has identified a regime where the receiver may anticipate the transmitter dynamics; i.e., the receiver dynamics may *lead* the transmitter. Voss has given analytic and numerical evidence of the occurrence of this regime in a system of two coupled scalar differential equations, in a unidirectional delayed coupling configuration. Masoller [16] has undertaken numerical work to identify a regime of anticipating synchronization in chaotic external-cavity semiconductor lasers. However, there have been no previous reports of the experimental observation of *anticipating chaotic synchronization* in any physical system.

In this Letter, we report the first experimental investigations, which demonstrate the anticipation of chaotic synchronization using an external-cavity laser diode as the transmitter and a solitary laser diode as the receiver.

The experimental setup is shown in Fig. 1. Two single-mode, Fabry-Pérot laser diodes emitting at 830 nm were used as transmitter and receiver. The laser operating temperatures are stabilized using thermoelectric controllers to a precision of 0.01 K. The output of the lasers is coupled to fast photodetectors (Newport–AD-70xr) and monitored using a digital oscilloscope (LeCroy-LC564A). The optical isolators ensure that no feedback from the photodetector facets reaches the laser diodes. The transmitter (receiver) laser is biased at 1.08 (1.04) times the free-running threshold. The retardation time τ_C is 3.5 ns throughout the experiment. The transmitter laser is operated in an external-cavity configuration with the external reflectivity being 1.75×10^{-3} so as to drive the transmitter into the low-frequency fluctuations regime. Beam splitters BS1 and BS3 couple the master laser output to the slave

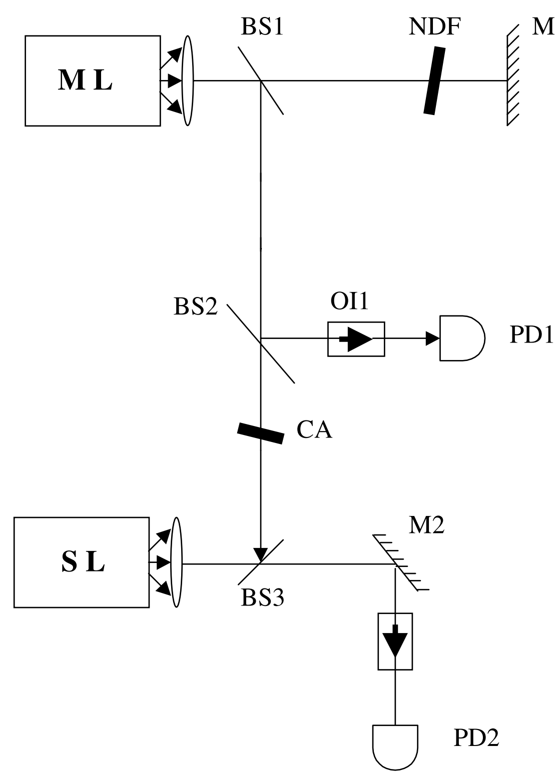

FIG. 1. TL, transmitter; RL, receiver; BS1–BS3, beam splitters; NDF, neutral density filter; OI1-2, optical isolators; M1-2, mirrors; CA, coupling attenuator; PD1 and PD2, photodetectors.

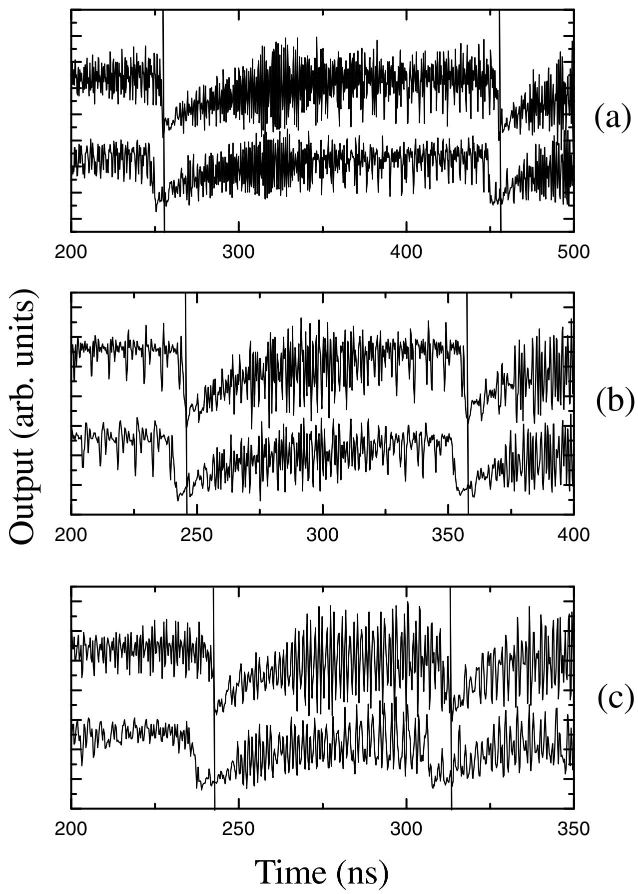

FIG. 2. Time traces of the transmitter (upper) and receiver (lower) laser output. The external-cavity round trip times are (a) 13.5 ns, (b) 6.7 ns, and (c) 3.5 ns. The vertical lines identify that the receiver laser is ahead of the transmitter laser. The transmitter laser time traces are shifted vertically for clarity.

laser. The coupling attenuator (CA) is used to control the amount of light coupled between the lasers. The coupling coefficient between the lasers is 0.14% throughout the experiment—this is the percentage of transmitter output power reaching the receiver and vice versa. This coupling coefficient is low enough to ensure that the receiver laser's facet reflectivity does not induce any dynamics in the transmitter output.

Figure 2 shows the time traces of the transmitter and receiver for external-cavity round trip times $\tau = 13.5$, 6.7, and 3.5 ns. In Fig. 2(a) it can be seen that close to 250 and 450 ns the receiver laser output falls and revives ahead of the transmitter laser. In Fig. 2(b) the same phenomenon is observed close to 250 and 350 ns. In Fig. 2(c) the same phenomena can be observed close to 250 and 300 ns. Hence the receiver laser is *leading* the transmitter laser by a time known as the "anticipation time," τ_A, which is measured to be 3.5 ns using the digital oscilloscope.

The measurement of anticipation time was confirmed by studying the quality of synchronization between the transmitter and receiver output. The receiver laser output is plotted against the transmitter laser output so as to obtain the synchronization plot [10,12,13]. The synchronization plot is then least squares fitted to a straight line, and the slope (m) and its variation (Δm) are calculated. The inverse of the variation ($1/\Delta m$) represents the quality of the synchronization (S_Q). Good synchronization would be indicated by $m = 1$ and low variation (Δm) implying high synchronization quality. On the other hand, poor synchronization would give a relatively large variation (Δm) and hence a low synchronization quality. Because of the effects of anticipation, the synchronization quality would be expected to be high if the transmitter laser output is shifted relative to the receiver output by an appropriate time represented here as τ_S.

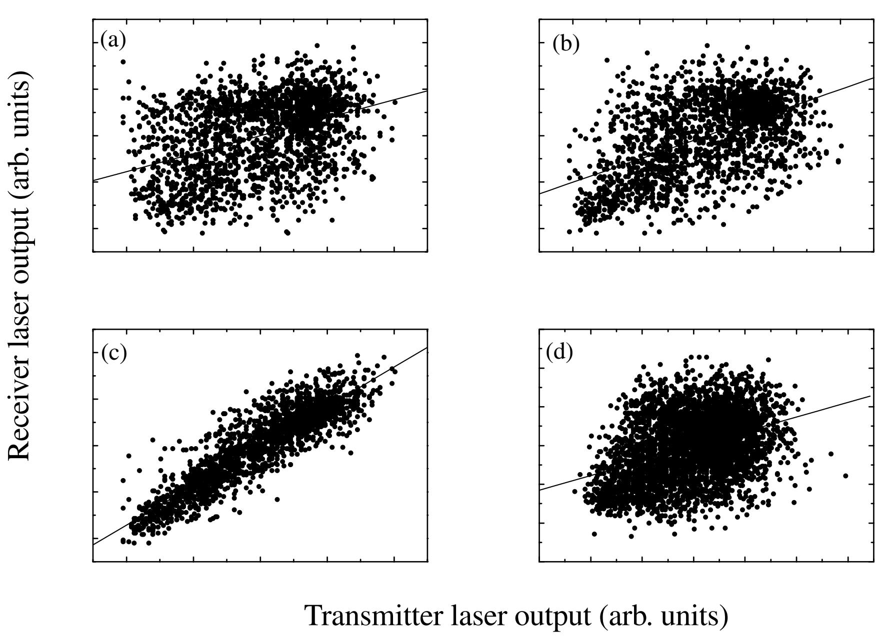

FIG. 3. Synchronization plots: receiver laser output plotted against transmitter laser output for various transmitter laser time shift, $\tau_S =$ (a) 0 ns, (b) 3.25 ns, (c) 3.50 ns, and (d) 3.75 ns. It is observed that the synchronization plot is close to straight line when the transmitter laser output is shifted by 3.5 ns in time. The straight lines are the least-squares fitted data.

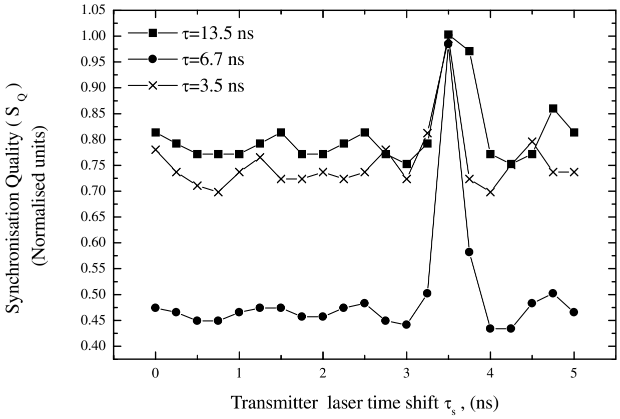

FIG. 4. Synchronization quality as a function of shift in transmitter laser output for external-cavity round trip times, $\tau = 13.5$ ns (■), 6.7 ns (●), and 3.5 ns (×).

The receiver laser output is plotted against the transmitter laser output and the synchronization plot for $\tau_S = 0$ is shown in Fig. 3(a), which, as expected, indicates poor synchronization. In Figs. 3(b), 3(c), and 3(d) synchronization plots are presented for $\tau_S = 3.00$, 3.50, and 3.75 ns, respectively. It is evident that the best synchronization is achieved for a transmitter laser time shift $\tau_S = 3.50$ ns. This confirms the occurrence of anticipating chaotic synchronization between the receiver and the transmitter with an anticipation time $\tau_A = 3.5$ ns.

In order to demonstrate the significance of the anticipation time, measurements were made of the synchronization quality S_Q, for three different external-cavity round trip times $\tau = 13.5$, 6.7, and 3.5 ns. Figure 4 shows the dependence of the (normalized) synchronization quality (S_Q) on the transmitter laser time shift τ_S. It is seen that the synchronization quality, in all cases, shows a sharp maximum at $\tau_S = 3.5$ ns. This indicates that the receiver laser is leading the transmitter laser by 3.5 ns irrespective of the external-cavity round trip time.

In conclusion, we report for the first time the occurrence of anticipating synchronization using chaotic semiconductor diode lasers. The time by which the receiver laser leads the transmitter laser (anticipation time) is found not to depend on the external-cavity round trip time. Such an observation of anticipating chaotic synchronization opens opportunities for application in various fields of interest, especially in optical communications, in information processing, and in controlling delay induced instabilities in a wide class of nonlinear systems.

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