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Synchronization of chaos in semiconductor lasers subject to polarization-rotated time-delayed feedback

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Abstract– We numerically investigate the detailed characteristics of chaos synchronization in semiconductor lasers subject to polarization-rotated optical feedback. The emission of the dominant TE mode of a drive laser is rotated 90 degrees and fed back to the laser with time delay. The polarization-rotated TE mode is also injected with time delay into the TM mode of a second laser. Two types of synchronization with different time-lags are found, as in the case for synchronization in semiconductor lasers with normal (non polarization-rotated) optical feedback. However, neither of the two types of synchronization requires matching of optical carrier frequency between the two lasers.

1. Introduction

Chaos synchronization has attracted interest for its potential applications to secure communications and spread spectrum communications [1]. Semiconductor lasers subject to delayed optical feedback are good candidates for use in practical applications due to their very fast (GHz range) and high dimensional chaotic dynamics and compatibility with already existing optical communication systems [2,3]. However, synchronization of chaotic signals generated in semiconductor lasers using "coherent" (optical-phase-dependent) feedback also requires coherent optical injection into the receiver laser to achieve locking of optical carrier frequency between the two lasers. It is very difficult to guarantee such a coherent coupling into the receiver system after transmission of a chaotic carrier over long distance through optical fiber. Therefore, the realization of high-speed synchronized chaos which does not depend on coherent injection to the receiver laser is highly desirable for practical applications.

The use of semiconductor lasers subject to "incoherent" optical feedback directly acting only on the carrier density in the laser rather than the optical field could be a way to fulfill the above-mentioned requirement. Semiconductor lasers with incoherent optical feedback have previously been studied theoretically using rate equation models [4], and polarization rotated feedback has been proposed [5,6] as a method to realize this theoretical concept experimentally. In these theoretical models the intensity of the feedback signal directly interacts with the carrier density. These models are rather similar to the model for semiconductor lasers with optoelectronic feedback [7], where the intensity of feedback signal is directly applied to the injection current of the semiconductor laser.

Some experiments on the dynamics of a semiconductor laser with polarization rotated feedback have been performed [6,8,9]. Experimental observation of chaos synchronization in semiconductor lasers with polarization-rotated optical feedback has also been reported quite recently [10]. However, a detailed characterization and investigation of the synchronization dynamics of semiconductor lasers subject to polarization rotated feedback is still lacking. In particular, the question of how polarization-rotated optical feedback corresponds to incoherent optical feedback in the sense of Refs. [4-6] is an important issue. Heil *et al.* showed that the dynamics of a semiconductor laser with polarization-rotated optical feedback did not correspond to the previous incoherent models in Refs. [4-6], and that a model including two polarization modes was needed to explain the behavior observed in experiments [9].

In this study we numerically investigate the characteristics of chaos synchronization in semiconductor lasers subject to polarization-rotated optical feedback using the two-mode model introduced in Ref. [9]. We explicitly take into account two polarization modes without explicitly assuming an incoherent feedback effect and clarify the characteristics of chaos synchronization.

2. Numerical calculation

2.1. Model

Our numerical model is shown in Fig. 1. We assume two single-mode semiconductor lasers (drive and response lasers). Both of the solitary semiconductor lasers exhibit single Transverse-Electric (TE) mode emission with high Transverse-Magnetic (TM) mode suppression. The delayed optical feedback is provided by an external optical loop circuit which polarizes the drive laser beam, rotates this polarization by 90 degrees, and re-injects this polarization-rotated beam back into the drive laser. The delay time is given by the round trip time of the light in the loop, and amounts to τ_d = 6.67 ns. The individual optical components are the following. An optical isolator (ISO) is used to achieve one-way loop propagation. A half wave plate (λ/2) rotates the polarization direction of the

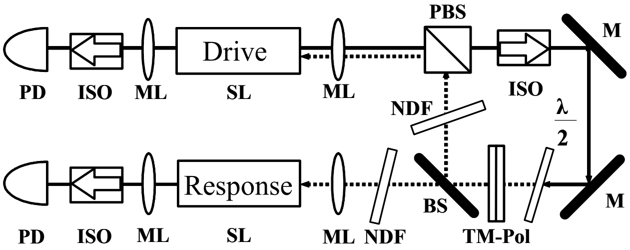

Fig. 1 Model for synchronization of chaos in two semiconductor lasers subject to polarization-rotated optical feedback. The semiconductor lasers oscillating mainly in the TE mode are subject to delayed polarization-rotated optical feedback and injection into the TM mode of the lasers. BS, beam splitter; ISO, optical isolator; M, mirror; ML, microscopic lens; NDF, neutral density filter; PBS, polarization beam splitter; PD, photodetector; SL, semiconductor laser; TM-Pol, polarizer along TM direction; $\lambda/2$, half wave plate. Solid line, TE-polarization mode; dotted line, TM-polarization mode.

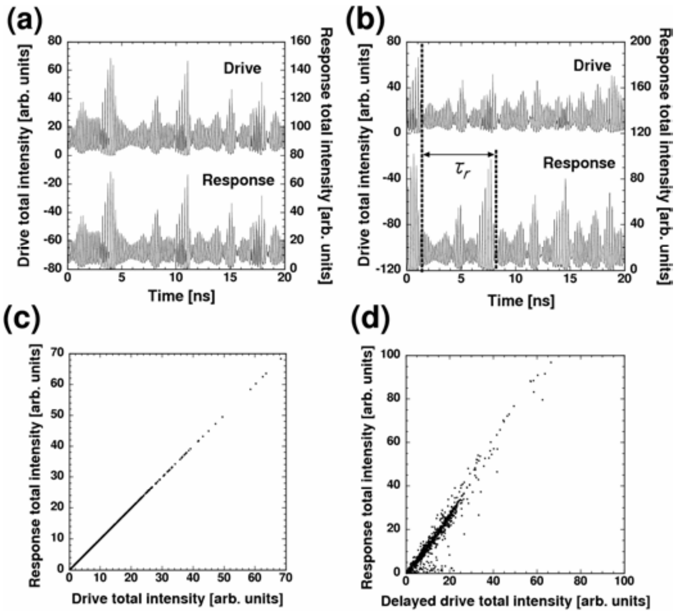

Fig. 2 Temporal waveforms and their correlation plots of the drive and response lasers at (a),(c) $\kappa_r = \kappa_d$ and (b),(d) $\kappa_r = 3\kappa_d$. (a),(c) complete synchronization. (b),(d) strong-injection synchronization. The drive waveform in (d) is shifted by τ_r in order to compensate the delay time between the two waveforms.

drive laser beam by 90 degrees from TE mode to TM mode, and a polarizer (TM-Pol) is used to ensure only TM-mode returns to the drive laser. The rotated laser beam with TM-mode is divided into two beams at a beam splitter. One of them is fed back to the drive laser through a polarization beam splitter (PBS) which feeds the outgoing TE beam into the loop, and feeds the returning TM beam back into the drive laser. The other beam is injected into the TM mode of the response laser for synchronization. The drive and response lasers are subject to the polarization rotated (TM-mode) optical feedback and injection, respectively. Two neutral density filters (NDF) control the strength of optical feedback and injection for the drive and response lasers. One facet of the lasers is used to provide the optical feedback and injection, and the other facet is used for detection of temporal dynamics. The temporal dynamics are detected by two photodetectors. Two optical isolators are used to eliminate the reflection beam from the photodetectors. We use a numerical model corresponding to Fig. 1. We use a two-polarization-mode dynamical model, allowing for the dynamics of the TM mode as well as the TE mode in the semiconductor laser [9].

2.2 Temporal waveforms

We calculated the temporal waveforms of the drive and response lasers with no detuning of optical frequency, as shown in Fig. 2. The delay time is set to be identical between the two lasers. Complete synchronization is observed at the identical parameter values as shown in Fig. 2(a). When the injection coefficient κ_r is increased, we cannot observe complete synchronization. However, the drive waveform delayed by τ_r is synchronized with the response waveform at $\kappa_r = 3\kappa_d$, which corresponds to strong-injection synchronization, as shown in Fig. 2(b). Figures 2(c) and 2(d) show the correlation plots between the drive and response waveforms corresponding to Figs. 2(a) and 2(b), respectively. The drive waveform in Fig. 2(d) is shifted by τ_r in order to compensate the delay time between the two waveforms. The correlation is very high for the complete synchronization in Fig. 2(c), whereas the correlation plots are scattered from the perfect correlation line in Fig. 2(d). We thus found two types of chaos synchronization in semiconductor lasers with polarization-rotated optical feedback, as in the case for synchronization in semiconductor lasers with normal (non polarization-rotated) optical feedback.

2.3. Cross correlation

To investigate the characteristics of synchronization, we quantitatively define the synchronization parameter as the cross correlation C of two temporal waveforms normalized by the product of their standard deviations: i.e.,

$$C = \frac{\left\langle (I_d - \bar{I}_d)(I_r - \bar{I}_r) \right\rangle}{\sigma_d \sigma_r}, \qquad (1)$$

where I_d and I_r are the total intensities of the drive and response waveforms, $\bar{I}_d$ and $\bar{I}_r$ are the mean values of the drive and response waveforms, and σ_d and σ_r are the standard deviations of the drive and response waveforms, respectively. The angle brackets denote time averaging. C =1 implies the best synchronization, whereas C =0 implies no synchronization.

We investigate the degree of synchronization when the injection strength or the detuning of the optical frequency between the two lasers is changed. The ratio of the injection coefficient to the feedback coefficient is defined as $\kappa = \kappa_r / \kappa_d$. The detuning Δf of the optical frequency between the two lasers is also calculated.

We systematically investigate the synchronization characteristics by changing both κ and Δf simultaneously. The two dimensional maps of the cross correlation for complete synchronization (between $I_d(t)$ and $I_r(t)$) and strong-injection synchronization (between $I_d(t-\tau_r)$ and $I_r(t)$) as functions of κ and Δf are shown in Figs. 3(a) and 3(b). The entire characteristics of synchronization on the κ-Δf plane can be seen in these maps. For complete synchronization shown in Fig. 3(a), there is a continuous narrow region for good synchronization, which includes the parameter matching condition (κ=1.0, Δf=0.0). Even in the presence of the detuning, good synchronization can be obtained by adjusting the injection strength. Good synchronization can be maintained in the presence of positive detuning by decreasing the injection strength, whereas the injection strength must be increased in the case of negative detuning for good synchronization. This asymmetric feature may result from the α -parameter (linewidth enhancement factor) of semiconductor lasers. For strong-injection synchronization shown in Fig. 3(b), wide synchronization region is observed at large injection strength. The threshold for synchronization in terms of κ depends on the detuning: the threshold becomes small at positive detuning and becomes large at negative detuning. These characteristics of the two types of chaos synchronization has never been observed in the incoherent numerical models [4-6]. We found these interesting features of chaos synchronization by using the two-polarization-mode model for semiconductor lasers with polarization-rotated optical feedback.

2.4. Actual Detuning

One of the important questions in our model is whether injection locking, locking of the optical frequency of the two lasers, occurs with chaos synchronization. To answer this question, we calculated the actual detuning of the optical frequency between the two lasers. The actual detuning is plotted as functions of κ and Δf as shown in Fig. 4. It can be seen that the actual detuning remains the

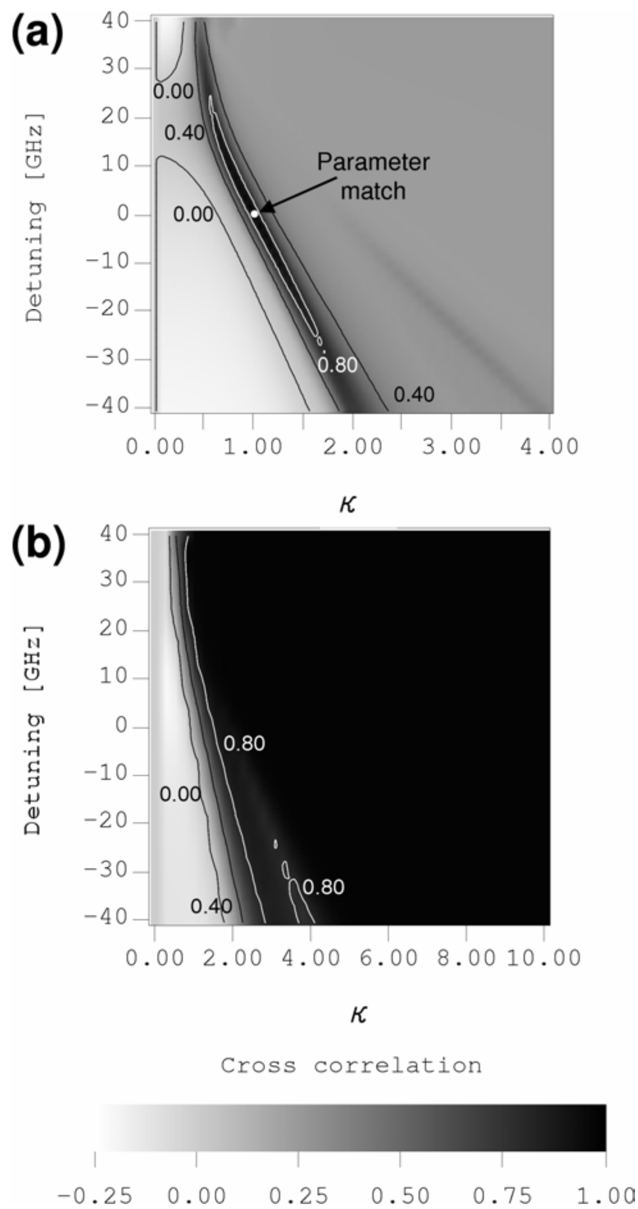

Fig. 3 Two-dimensional map of cross correlation for (a) complete synchronization and (b) strong-injection synchronization as functions of the ratio of the injection strength to the feedback strength κ and the detuning of optical frequency between the two lasers Δf . Cross correlation is calculated from the two temporal waveforms of (a) $I_d(t)$ and $I_r(t)$, and (b) $I_d(t-\tau_r)$ and $I_r(t)$. The dot in (a) corresponds to the parameter matching condition. Note that the horizontal axes of (a) and (b) are in different ranges.

same as the initial detuning Δf independent of the value of the injection strength κ. We obtained the same result as Fig. 4 when we calculated the actual detuning between the TE modes of the drive and response lasers. Comparing with Fig. 3, it can be seen that the two types of chaos synchronization can occur even though the optical frequencies of the two lasers remain different. This is a significant difference compared to chaos synchronization in semiconductor lasers with normal (non polarization-rotated) optical feedback, which requires locking of optical frequency.

3. Conclusion

We have investigated synchronization of chaos in semiconductor lasers subject to polarization-rotated optical feedback. Both the feedback signal for the drive laser and the injection signal for the response laser are polarization-rotated at 90 degrees. We found two types of synchronization, as in the case for synchronization in semiconductor lasers with normal (non polarization-rotated) optical feedback. The two regimes are referred to as complete synchronization regime and strong-injection synchronization regime. The two types of synchronization can be distinguished by the difference in time lag with respect to the injection signal. For both types, synchronization can be observed even in the presence of large detuning of optical frequency. In the complete synchronization regime, which includes the case where all parameters are closely matched, chaos synchronization can be maintained for large detunings if there is an appropriate adjustment of the injection strength. In the case of strong-injection synchronization, which occurs when the optical power injected into the response laser is much stronger than the self-feedback in the drive laser, chaos synchronization can be maintained for large detunings even for fixed large injection strength.

In the sense that chaos synchronization in semiconductor lasers with polarization-rotated optical feedback does not require matching of optical frequency, it is significantly different from the chaos synchronization in semiconductor lasers with normal (non polarization-rotated) optical feedback, which does require locking of optical frequency. This feature could be very useful for real-world implementations of secure communication systems using chaos synchronization.

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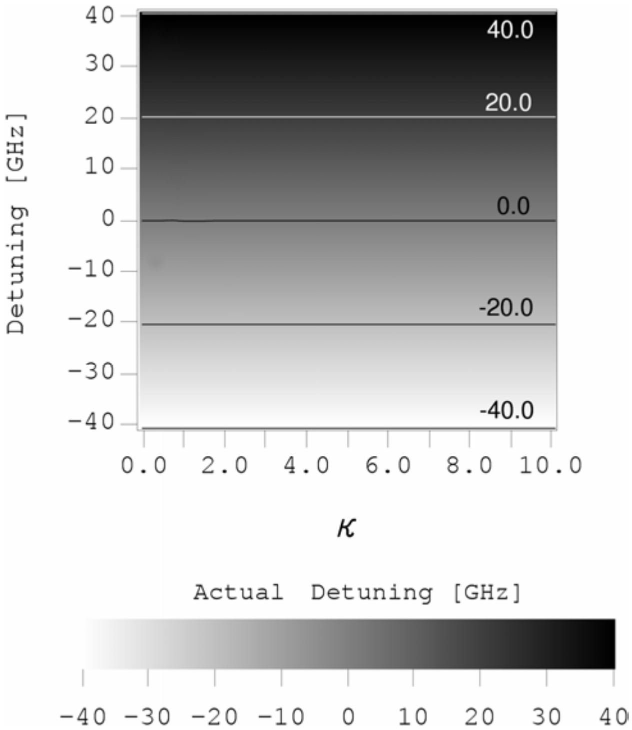

Fig. 4 Actual detuning of optical frequency between the two lasers as functions of the ratio of the injection strength to the feedback strength κ and the initial detuning of optical frequency between the two lasers Δf.

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