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Experiment on common-signal-induced synchronization with constant-amplitude random-phase drive signal

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Abstract– We experimentally observe common-signal-induced synchronization by an optical injection from a drive laser with constant-amplitude random-phase to two response lasers. The cross correlation between the drive laser and one of the response lasers is very small (~ 0.2), whereas the cross correlation between the two response lasers is large (~ 0.9). We investigate the dependence of synchronization on parameter values in wide parameter ranges.

1. Introduction

Synchronization between uncoupled nonlinear dynamical systems subject to a common chaotic drive signal has been studied in laser experiments [1,2] Synchronization between two response lasers with high correlation can be achieved, whereas the correlation between the drive and response lasers is relatively low. This phenomenon could be useful for applications of hardware-oriented information-theoretic security systems [3]. For these applications, it is required to have low correlation between the drive and response lasers, while high correlation is achieved between the two response lasers. In the previous experiments [1,2], however, the cross correlation between the drive and response lasers is around 0.6 since similar chaotic laser systems with similar frequency components are used for the drive and response laser systems.

Instead of using a chaotic drive signal with intensity fluctuation, the use of a drive light with constant amplitude but randomly fluctuating optical phase can be introduced as a common injection signal. This type of light signal is referred to as a constant-amplitude random-phase (CARP) signal. It has been shown in numerical simulations that it is possible to obtain synchronization of two semiconductor lasers subject to a common CARP light [4].

In this study, we experimentally observe synchronization of two semiconductor lasers subject to a common CARP light. It is expected to have small correlation between the drive and one of the response lasers by using the CARP light since the amplitude of the drive signal is almost constant. We investigate the dependence of synchronization on the laser parameters such as the optical wavelength detuning and the relaxation oscillation frequency.

2. Experimental Setup

Figure 1 shows our experimental setup for the synchronization of two semiconductor lasers by the injection of a common CARP light. We use three distributed-feedback (DFB) semiconductor lasers (the optical wavelength of 1547 nm). One laser is used for a Drive laser and the other two lasers are used for Response 1 and 2 lasers. The injection current and temperature of the semiconductor lasers are adjusted by a controller. The optical wavelength of the semiconductor lasers is precisely controlled by the temperature of the laser with a ratio of 0.097 nm/K. The resolution of the temperature control is 0.01 K. The lasing thresholds of injection current I_{th} are 10.57 mA (Drive), 9.38 mA (Response 1), and 9.49 mA (Response 2), respectively.

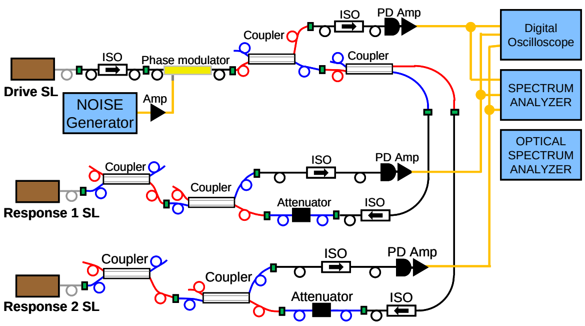

Fig. 1 Experimental setup for the synchronization of semiconductor lasers subject to a common constant-amplitude random-phase (CARP) light. Amp: electric amplifier, ISO: optical isolator, PD: photodetector, SL: semiconductor laser.

A light from the Drive laser is injected into an optical isolator (ISO) and a phase modulator (PM) unidirectionally. The optical phase of the Drive laser light is randomly modulated by the PM and a noise generator, and CARP light can be generated. The CARP light from the Drive laser is divided by a fiber coupler. One light is injected into an optical isolator and a photodetector (PD). The other light is divided by another fiber coupler and injected into the Response 1 and 2 lasers unidirectionally through an optical isolator. The light power is adjusted by using an attenuator. The Response 1 and Response 2 are set to have the same parameter values. The lights from the two Response lasers are injected into PDs through fiber couplers and converted into electric signals. The electric signals are amplified by electric amplifiers (Amp), connected to a digital oscilloscope and a radio-frequency (RF) spectrum analyzer to observe temporal waveforms and RF spectra, respectively. The optical spectra are observed by using an optical spectrum analyzer.

3. Experimental Results

3.1. Common-signal-induced synchronization

We set the relaxation oscillation frequencies of the Drive and Response lasers by adjusting the injection current of the lasers. The relaxation oscillation frequencies between the Response 1 and Response 2 lasers are matched at 2.0 GHz, whereas that between the Drive (2.5 GHz) and Response lasers are mismatched. At this condition, the injection current is 14.00 mA (1.32 I_{th}) for the Drive, 12.30 mA (1.31 I_{th}) for the Response 1, and 12.68 mA (1.34 I_{th}) for the Response 2 lasers, respectively. The optical phase of the Drive laser is randomly modulated by the noise generator whose bandwidth is 1.5 GHz.

We set the optical wavelength of the Drive and Response lasers by adjusting the temperature of the lasers. Figure 2(a) shows the optical spectra of the solitary three lasers without optical injection from the Drive laser. We set the optical wavelength of 1547.954 nm for the Drive, 1546.936 nm for the Response 1, and 1546.935 nm for the Response 2 lasers, respectively. The optical wavelength detuning between Drive and Response 1 is $\Delta\lambda_{R1D}$ = $\lambda_{Response\ 1}$ - λ_{Drive} = -0.018 nm (-2.25 GHz) and that between Drive and Response 2 is $\Delta\lambda_{R2D}$ = $\lambda_{Response\ 2}$ - λ_{Drive} = -0.019 nm (-2.38 GHz). Figure 2(b) shows the optical spectra of the three lasers in the presence of optical injection from the Drive laser to the Response 1 and Response 2 lasers under injection locking. Injection locking is a phenomenon where the optical wavelengths of two lasers are matched when the wavelengths of two lasers are close to each other and the light with longer wavelength is injected to the laser with shorter wavelength in coherently coupled semiconductor lasers [5]. The optical spectra of the Response 1 and 2 lasers are matched to that of the Drive laser at 1546.954 nm, as shown in Fig. 2(b). Common-signal-induced synchronization can be achieved when the optical wavelengths of the three lasers are matched under injection locking.

Figure 3 shows the temporal waveforms and the correlation plot of the Drive and Response 1 with optical injection from the Drive to the Response lasers under injection locking. A fluctuation of the Drive laser output cannot be clearly observed because only the phase modulation is applied to the Drive signal as shown in Fig. 3(a). A tiny fluctuation of the Drive is caused by the relaxation oscillation of the semiconductor laser. The temporal waveforms between the Drive and Response 1 are different as shown in Fig. 3(a). The correlation plot of Fig. 3(b) also shows that the correlation is low between the Drive and Response laser intensities.

Figure 4 shows the temporal waveforms and the correlation plot of the Response 1 and Response 2 with optical injection from the Drive to the Response lasers under injection locking. The temporal waveforms of the Response 1 and Response 2 are almost the same fluctuation, indicating high-quality synchronization. Synchronization can be clearly seen in the correlation plot of Fig. 4(b).

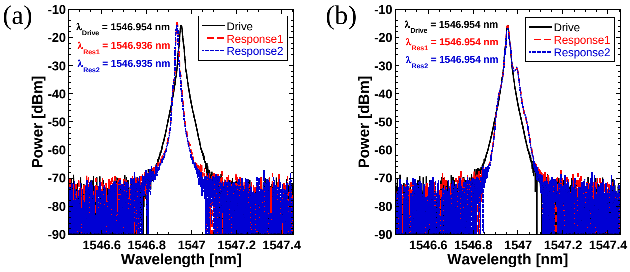

Fig. 2 Experimental result of optical spectra (a) without and (b) with optical injection from the Drive to Response lasers. Solid curve: Drive, dotted curve: Response 1, dashed curve: Response 2.

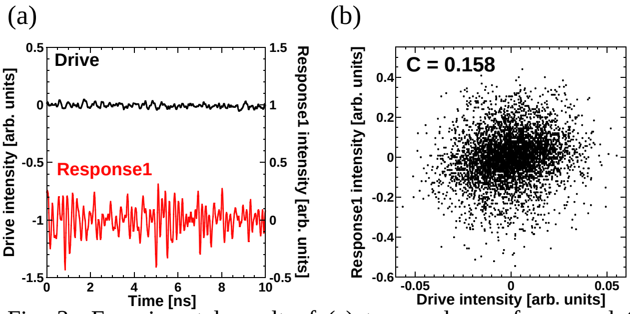

Fig. 3 Experimental result of (a) temporal waveforms and (b) corresponding correlation plots for the outputs of the Drive and Response 1 lasers.

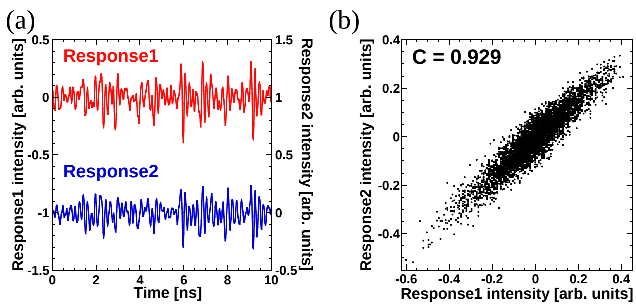

Fig. 4 Experimental result of (a) temporal waveforms and (b) corresponding correlation plots for the outputs of the Response 1 and Response 2 lasers.

We use the cross correlation coefficient to quantitatively evaluate the quality of synchronization. The equation is described as follows,

$$C = \frac{\left\langle \left(I_1(t) - \bar{I}_1\right)\left(I_2(t) - \bar{I}_2\right)\right\rangle}{\sigma_1 \cdot \sigma_2} \qquad (1)$$

where I_1, I_2 are temporal waveforms of the output intensities of Response 1 and 2 lasers, respectively, $\bar{I}_1, \bar{I}_2$ are their mean values, σ_1, σ_2 are their standard deviations, and the angle brackets denote time averaging. When the cross correlation value is 1, the best synchronization is obtained.

The cross correlation value between the Drive and Response 1 lasers shown in Fig. 3(b) is 0.158 and low correlation is observed. On the other hand, the cross correlation value between the Response 1 and Response 2 lasers shown in Fig. 4(b) is 0.929 and high correlation is observed.

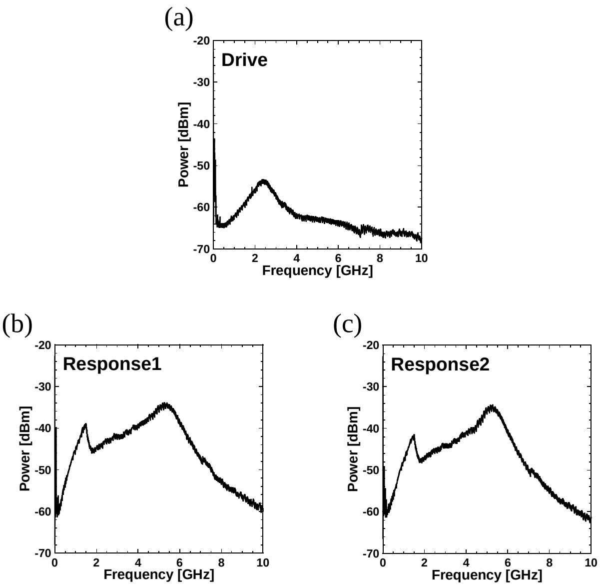

Fig. 5 Experimental result of RF spectra for (a) Drive, (b) Response 1, and (c) Response 2 lasers.

Figure 5 shows the RF spectra of the Drive, Response 1, and Response 2 lasers. The RF spectra of the Response 1 and Response 2 (Fig. 5 (b), (c)) are very similar, whereas those of the Drive and Response 1 (Fig. 5 (a), (b)) are different. The peak frequencies of the Response 1 and Response 2 are 1.5 GHz and 5.3 GHz. The peak frequency of 1.5 GHz corresponds to the bandwidth of the noise signal used for random phase modulation. We speculate that the peak frequency of 5.3 GHz results from the nonlinear interaction between the relaxation oscillation frequency and the optical carrier frequency detuning in the Response lasers. On the other hand, the peak of the RF spectrum of the Drive corresponds to small relaxation oscillation, whose frequency is 2.4 GHz. These results confirm that high-quality synchronization between the Response 1 and Response 2 lasers is achieved, however, the correlation between the Drive and Response is very low. We have found that common-signal-induced synchronization in semiconductor lasers subject to a constant-amplitude random-phase drive signal can be achieved experimentally.

3.2. Parameter dependence of synchronization

Next we investigate the dependence of synchronization on parameter values. We set the relaxation oscillation frequency of 1.5 GHz for the Drive laser and that of 1.0 GHz for the Response 1 and Response 2 lasers. The cross correlation is measured when the optical wavelength detuning is changed. The solid curve of Fig. 6 shows the cross correlation between the Response 1 and Response 2 lasers as a function of the initial optical wavelength detuning, which is between the Drive and Response 1 lasers without optical injection ($\Delta\lambda_{RD} = \lambda_{Response} - \lambda_{Drive}$). The dashed curve of Fig. 6 indicates the optical wavelength detuning between the Drive and Response 1 lasers with optical injection. When $\Delta\lambda_{RD}$ is increased from negative to positive values, injection locking is achieved at $\Delta\lambda_{RD}$ = -0.089 nm, and the cross correlation is increased rapidly. The maximum cross correlation is obtained at $\Delta\lambda_{RD}$ = -0.021 nm, and the correlation value starts decreasing as $\Delta\lambda_{RD}$ is increased. The injection locking range is defined as the region in which the absolute value of the optical wavelength detuning with optical injection is less than 0.005 nm. The region with large cross correlation almost corresponds to the injection locking range (-0.089 nm < $\Delta\lambda_{RD}$ < 0.046 nm) as shown in Fig. 6.

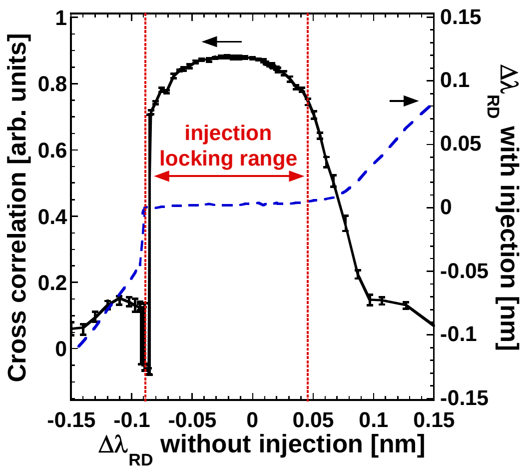

Fig. 6 Experimental result of the cross correlation between the Response 1 and Response 2 lasers (solid curve) and the optical wavelength detuning between the Drive and Response 1 lasers with optical injection (dashed curve) as a function of the initial optical wavelength detuning between the Drive and Response 1 lasers ($\Delta\lambda_{RD}$). The dotted lines indicate the injection locking range, where the two optical wavelengths are matched to each other due to the optical injection.

Figure 7 shows the cross correlation between the Drive and Response 1 lasers (solid curve) and that between the Response 1 and Response 2 lasers (dotted curve) as a function of the relaxation oscillation frequency of the Drive laser. We set the relaxation oscillation frequency of 2.0 GHz for the two Response lasers. The cross correlation between the two Response lasers is small for small relaxation oscillation frequencies of the Drive laser because the injection light power of the Drive is not enough to achieve injection locking. As the relaxation oscillation frequency of the Drive laser is increased, both the cross correlation between the Drive and Response 1 lasers and that between the two Response lasers are increased. The cross correlation between the Response 1 and Response 2 becomes the maximum value of 0.940 for the relaxation oscillation frequencies of 1.5 GHz for the Drive laser, while the cross correlation between the Drive and Response 1 remains the low value of 0.122.

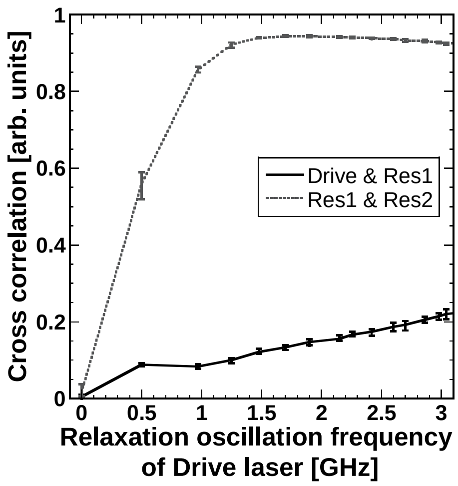

Fig. 7 Experimental result of the cross correlation value between the Drive and Response 1 lasers (solid curve) and that between the Response 1 and Response 2 lasers (dotted curve) as a function of the relaxation oscillation frequency of the Drive laser.

4. Conclusion

We have experimentally investigated common-signal-induced synchronization with a constant-amplitude random-phase (CARP) drive signal in semiconductor lasers. Common-signal-induced synchronization is achieved by injection locking between the Drive and two Response lasers. The cross correlation between the Drive and Response 1 is small (~0.2), while the cross correlation between two Responses is large (~0.9). We have also investigated the dependence of synchronization on laser parameter values and found that common-signal-induced synchronization can be observed under the condition of the optical wavelength matching by injection locking.

Acknowledgments

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