Frequency dependence of common-signal-induced synchronization in semiconductor lasers with constant-amplitude and random-phase light

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Abstract– We experimentally observe common-signal-induced synchronization between two single-mode semiconductor lasers with constant-amplitude and random-phase modulation. We investigate the frequency dependence of synchronization on the parameter values over wide parameter ranges. We use low-pass filters with different cut-off frequencies to change the bandwidth of random-phase-modulation of the drive signal. We found that high cross correlation (~0.94) between the two response lasers can be observed when the cut-off frequency is equal to or higher than 5 GHz. On the other hand, the correlation between the two response lasers is relatively low (~0.75) when the cut-off frequency is lower than 5 GHz.

1. Introduction

Information security is very important in communication and computer systems. Schemes for secure key distribution rely on two main security paradigms, computational security and information-theoretic security. Computational security is based on the assumed hardness of computational problems. On the other hand, information-theoretic security [1] is based on probability theory and on the fact that an adversary's information is limited. Recently, Information-theoretic security key distribution has been proposed using generation of correlated random bit sequences in synchronization of semiconductor lasers [2,3,4]. This scheme is implemented by using common-signal-induced synchronization in semiconductor lasers with constant-amplitude and random-phase light (CARP light) [5,6]. The security in this scheme is based on the physical limitation that the common random light has a broad fluctuation bandwidth which is too broad to completely observe its fast temporal variation with current technology. Even though some experimental results have been reported, the fluctuation bandwidth of the common random light is limited to less than 1.5 GHz [7]. Therefore, it can be expected to improve security by using broader common random light. However, there has been no report on common-signal-induced synchronization with broad common random light.

In this study, we investigate the common-signal-induced synchronization between two semiconductor lasers with constant-amplitude and random-phase light to clarify the dependence of the synchronization quality on the modulation bandwidth of the drive signal.

2. Common-signal-induced synchronization

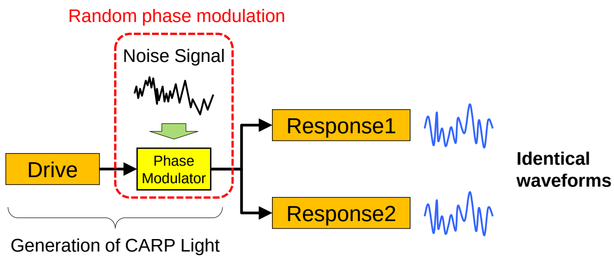

Fig. 1 Schematic of common-signal-induced synchronization with constant-amplitude and random-phase light.

Common-random-signal induced synchronization is a key technique for secure key distribution scheme [7]. The concept of common random-signal induced synchronization with CARP light is shown in Fig. 1. A drive signal from a laser system (called Drive laser) is injected into two laser systems (called Response 1 and 2 lasers) that have different initial conditions. The outputs from the two Response lasers injected from the common drive signal are identically synchronized, even though the outputs of the Drive and Response lasers are different [8,9]. In this study, we use constant-amplitude and random-phase light (CARP light) as a common drive signal. The CARP light can be generated by using a phase modulator with a white Gaussian noise signal.

We change frequency bandwidth of the noise signal that is used to modulate the optical phase of the drive signal. We perform an experiment on common-signal-induced synchronization with the CARP light, and investigate the synchronization quality between the two Response lasers.

3. Experimental setup

The experimental setup is shown in Fig. 2. We use three semiconductor lasers (Drive, Response 1, and Response 2) for common-signal-induced synchronization. The lasers are single-mode distributed-feedback (DFB) semiconductor lasers (NTT Electronics, the optical wavelength of 1547 nm). We use super-luminescent diode which has broad frequency bandwidth (> THz) for optical phase modulation of the Drive laser. The output light from the Drive laser (LD) is injected into an optical isolator (ISO) to transmit the light unidirectionally. We use the optical noise signal from the output of a super-luminescent diode (SLD). The optical phase of the drive signal is modulated randomly, and constant-amplitude and random-phase light (CARP light) is generated. The output light from SLD is injected into a photodiode (PD) unidirectionally through ISO. The power of the injection signal is adjusted by using an optical attenuator (ATT). The output of the SLD is transformed into an electric signal by PD and amplified by electric amplifies (Amp) to send to the optical phase modulator (PM). The bandwidth of the PM is 20 GHz. The frequency bandwidth of the optical noise from SLD is limited by a low-pass filter (LPF) after Amp. In the case without LPF, the frequency bandwidth is limited to 12 GHz by the frequency bandwidth of PD. We can change the random-phase-modulation bandwidth of the drive laser by using LPFs with different cut-off frequencies. The CARP light from the Drive laser is divided by a fiber coupler (FC). Each light is injected into the Response 1 and 2 lasers unidirectionally through ISO. The light power is adjusted by using ATT. The output waveforms of the three lasers are observed by using a digital oscilloscope.

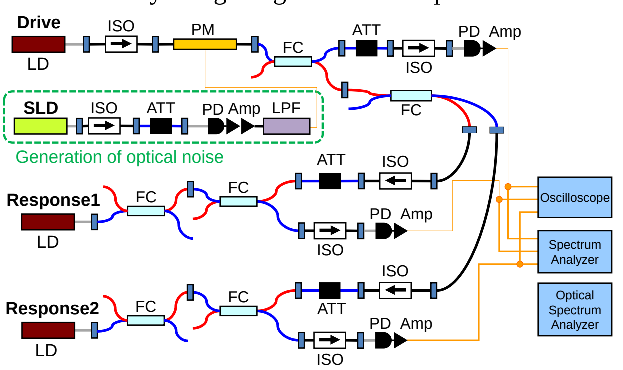

Fig. 2 Experimental setup of common-signal-induced synchronization with CARP light. Amp, electric amplifier; ATT, attenuator; FC, fiber coupler; ISO, optical isolator; LD, laser diode; LPF, low-pass filter; PD, photodiode; PM, phase modulator; SLD, super luminescent diode.

4. Generation of optical noise

We change the frequency bandwidth of the optical noise from the output of SLD by using four types of low-pass filters (LPF) whose cut-off frequencies are 1.5, 3.0, 5.0, and 8.0 GHz, respectively. We can change the random-phase-modulation bandwidth of the drive laser. The RF spectra of the output waveforms of SLD with the different low-pass filters are shown in Fig. 3. We adjust the light power of the SLD to match the standard deviations of the temporal waveforms from SLD with different low-pass filters. Figure 3(a) shows the RF spectra of the SLD with different low-pass filters. It confirms that the bandwidth of the optical noise from SLD can be changed by using the low-pass filters with different cut-off frequencies. Without low-pass filters, the RF spectra power gradually decreases over 10 GHz, limited by the bandwidth of PD. Figures 3(b) and 3(c) show the output waveforms from SLD with the low-pass filters (1.5 and 8.0 GHz). The observations confirm that high speed random-phase-modulation of drive laser is possible by using the optical noise with broad frequency bandwidth.

We generate optical noise signals by using low-pass filters (1.5, 3.0, 5.0, and 8.0 GHz) and without low-pass filter (12 GHz). The optical phase of the Drive laser is modulated by using these optical noises to generate CARP lights with different phase-modulation bandwidth.

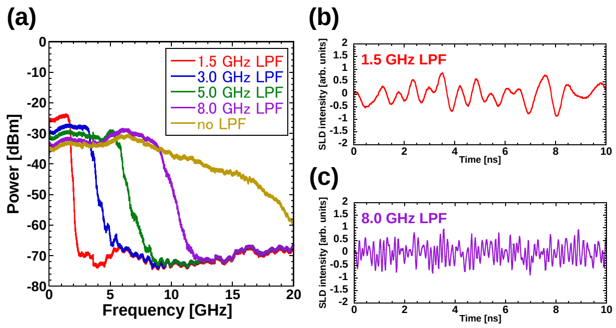

Fig. 3 Outputs of super-luminescent diode with low-pass filters (1.5, 3.0, 5.0 and 8.0 GHz). (a) RF spectra and (b),(c) temporal waveforms.

5. Experimental results

We experimentally investigate common-signal-induced synchronization when broadband phase-modulation noise is used for the drive laser. We introduce a measure of analog cross-correlation to evaluate the quality of synchronization. The analog cross-correlation value is calculated as follows:

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

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 of I_1, I_2, and < > indicate time averaging. $C_A = 1.0$ indicates identical synchronization, whereas $C_A = 0.0$ indicates no synchronization.

Figure 4 shows the temporal waveforms of the Response 1 and 2 lasers and their correlation plots. In Fig. 4(a) and (b), when the phase-modulation bandwidth of drive laser is 1.5 GHz, the temporal waveforms of the two Response lasers are weakly correlated and the amplitudes are small. On the other hand, for Fig. 4(c) and (d), when phase-modulation bandwidth of drive laser is 8.0 GHz, the temporal waveforms of the two Response lasers are strongly correlated and the amplitudes are larger than those in Fig. 4(a).

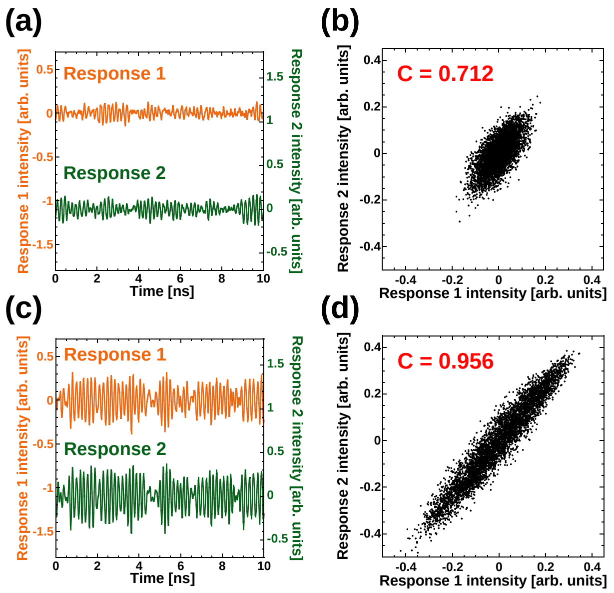

Fig. 4 Experimental results for the outputs of Response 1 and Response 2 lasers for the phase-modulation bandwidths of (a),(b) 1.5 GHz and (c),(d) 8.0 GHz. (a),(c) Temporal waveforms and (b),(d) corresponding correlation plots.

We investigate the frequency dependence of common-signal-induced synchronization. Figure 5 shows the cross correlation between the Response 1 and 2 lasers (black line) and the standard deviation of Response 1 laser (orange line) when the phase-modulation bandwidth of Drive laser is changed (1.5 ~ 12 GHz). In Fig. 5, the cross correlation value increases as the bandwidth of the phase-modulation increases. High cross correlation values (~0.94) between the two response lasers are observed when the phase-modulation bandwidth is equal to or higher than 5 GHz. On the other hand, the cross correlation values between the two Response lasers are relatively low (~0.75) when the phase-modulation bandwidth is lower than 5 GHz. The orange curve shows the standard deviation of Response 1 laser when the phase-modulation bandwidth is changed. In Fig. 5, large standard deviation of Response 1 laser is observed for the phase-modulation bandwidth equal to or higher than 5 GHz.

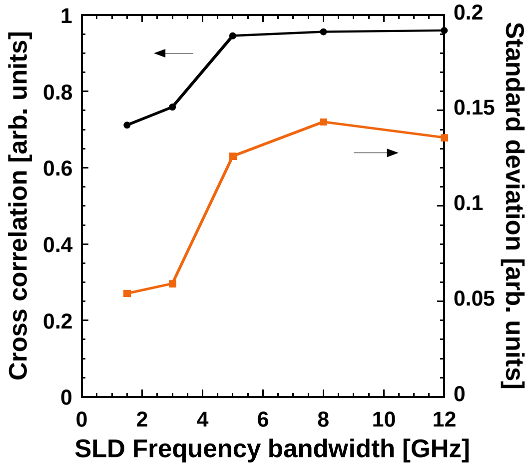

Fig. 5 Experimental results of the cross correlation between the Response 1 and Response 2 lasers (black line) and the standard deviation of the temporal waveform of the Response 1 laser (orange line) as a function of the bandwidth of the phase-modulation bandwidth.

We consider the dependence of the spectrum of the response laser on the modulation bandwidth. Figure 6 shows the RF spectra of Response 1 laser with optical injection by using low-pass filters (1.5 and 8.0 GHz). In Fig. 6, there are two peaks in the RF spectra of the Response 1 laser when phase-modulation bandwidth is set to 1.5 GHz. The frequency of the left peaks for the case of 1.5 GHz corresponds to the bandwidth of the noise signal used for random-phase modulation. This peak may result from the intensity-phase conversion in the response laser cavity. On the contrary, the peak frequency at 5.8 GHz corresponds to the detuning of the optical carrier frequency between the Drive laser and Response 1 laser with optical injection [6]. In the cases of phase-modulation bandwidth of 8.0 GHz, no peaks appear for low frequency regions and the peak at 5.8 GHz is high. The existence of the large peak at 5.8 GHz corresponds to large amplitude of the temporal waveform for the case of the phase-modulation bandwidth of 8.0 GHz.

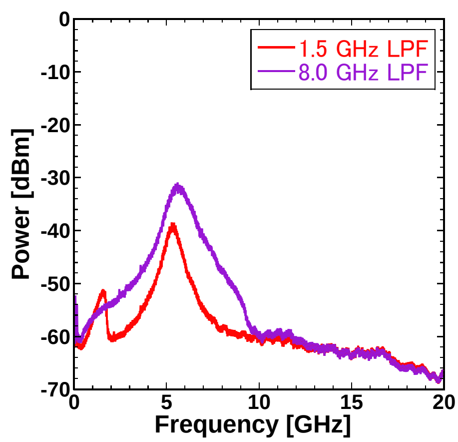

Fig. 6 Experimental results of the RF spectra for Response 1 laser for the phase-modulation bandwidths of 1.5 and 8.0 GHz.

6. Parameter dependence of synchronization for different bandwidths of random-phase modulation

We investigate the dependence of synchronization on laser parameter values for different phase-modulation bandwidths. We observe the change in the cross correlation when the optical injection strength from the Drive laser to each of Response lasers is changed. Figure 7 shows the cross correlation values between the Response 1 and 2 lasers as a function of the optical injection strength. The cross correlation becomes larger and reaches a constant value as the injection strength is increased. The common-signal-induced synchronization with CARP light is achieved with large optical injection power. In the case of the phase-modulation bandwidth of 1.5 GHz, the cross correlation is obtained about 0.7 with large optical injection power. On the contrary, in the case of the phase-modulation bandwidth of 8.0 GHz, the cross correlation can be observed about 0.9 with large optical injection power. Therefore, we found that high correlation can be observed for large phase-modulation bandwidth.

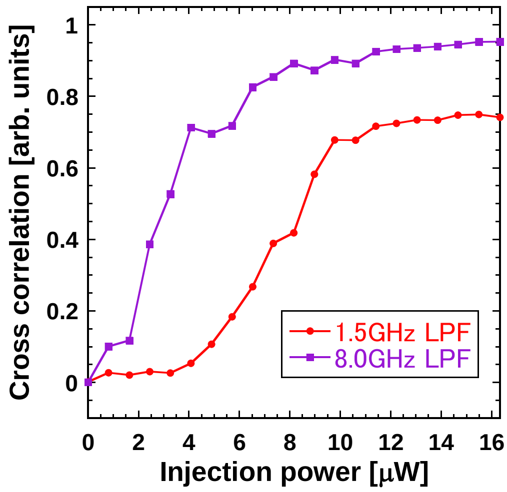

Fig. 7 Experimental result of the cross correlation between the Response 1 and Response 2 lasers as a function of the injection strength.

7. Conclusion

We experimentally investigated the parameter dependence of the random-phase-modulation bandwidth for common-signal-induced synchronization of single mode semiconductor lasers. We achieved common-signal-induced synchronization by using constant-amplitude and random-phase light as a common signal which has different phase-modulation bandwidth. High cross correlation (~0.94) between the two response lasers can be observed when the phase-modulation bandwidth is equal to or higher than 5 GHz. On the other hand, the correlation is relatively low (~0.75) when the phase-modulation bandwidth is lower than 5 GHz. We also investigated the dependence of synchronization on laser parameter values. We found that high correlation values are observed for large phase-modulation bandwidth.

Acknowledgments

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