Synchronization induced by common ASE noise in semiconductor lasers

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Abstract—We demonstrated experimentally the synchronization between two semiconductor lasers by the injection of common amplified spontaneous emission (ASE) light, emitted from a super luminescent diode. The synchronization was realized in the both cases of the semiconductor lasers with and without optical feedback. Note that the lasers can behave chaotically with optical feedback. The quality of the synchronization, measured by the cross-correlation coefficients of the two laser outputs, can be improved by increasing the injected ASE light. In addition, we show the condition of the optical spectra to achieve good synchronization.

1. Introduction

When several nonlinear oscillators are interacted each other, the oscillators can be synchronized in various way [1, 2]. Various systems such as neurons, ecological systems, and electric circuits can become such nonlinear oscillators. These phenomena have attracted many researchers and fundamental mechanisms have been revealed from viewpoints of nonlinear dynamics. In addition, there are potential applications in engineering field. For example, the synchronization in laser systems can be applied to communication systems since high-speed data communications are mainly implemented with the laser systems. In particular, the chaotic synchronization in drive-response configuration can be applied to secure communications, such as chaos masking and chaos modulation [3, 4].

From viewpoints of engineering applications and nonlinear physics, it is important to reveal the effects of noise in the synchronization since noise is inevitable in real physical devices and noise sometimes plays interesting roles in the synchronization. One example is common noise induced synchronization (CNIS), which is phenomenon that two nonlinear oscillators driven by common external noise are synchronized with each other [5, 6, 7, 8, 9, 10]. In the NOLTA 2013, we show experimentally that noise of a drive laser system can enhance synchronization in unidirectionally coupled laser systems. Moreover, it is also known that CNIS can occur in uncoupled laser systems driven by a common noise [11, 12]. However, the synchronization in laser systems driven by common amplified spontaneous emission (ASE) noise has yet to be well studied experimentally.

In this paper, we show the experimental demonstration of common noise induced synchronization of lasers by the injection of ASE noise. In Sec. 2, the experimental setup for our investigations is described. In Sec. 3, we show some experimental results that demonstrate the synchronization of laser systems driven by common noise. In Sec. 4, we summarize our results.

2. Experimental Setup

Figure 1 shows the experimental setup for our investigations of the common noise induced synchronization in semiconductor lasers. A super luminescent diode (SLD) emits ASE light, which is broadband and low-coherent. In some experiments, the ASE light is filtered by a band pass filter (FLT). The light is split into

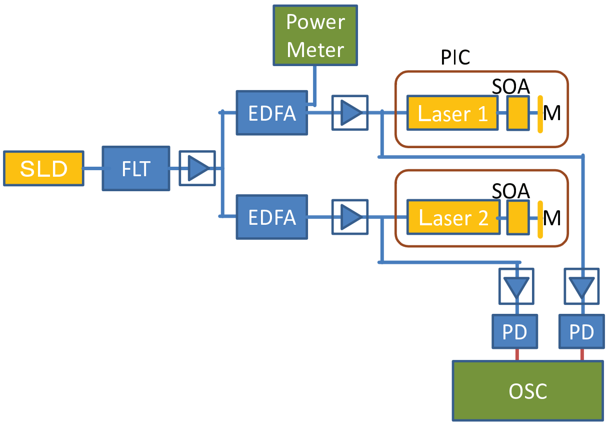

Figure 1: Schematic of experimental setup.

two and each light is amplified with each erbium doped fiber amplifier (EDFA). The intensity of each ASE light can be adjusted independently and the light is injected into two distributed-feedback (DFB) semiconductor lasers (Laser 1 and Laser 2). Note that we used the lasers which are embedded in photonic integrated circuits (PICs). The details of PICs are described in Sec. 3.2. The conditions of the two DFB lasers are set as same as possible. The ratios of injection currents (denoted by J) to threshold currents (denoted by J_{th}) are set to be same and the optical wavelengths of the two DFB lasers are set to be matched by tuning their temperatures. The outputs of two DFB lasers are transformed into radio-frequency signals by photodetectors (PDs) with a bandwidth of 12.5 GHz. We observed temporal waveforms of the two semiconductor lasers by an oscilloscope (OSC) with a bandwidth of 16 GHz at 50 GSample/s.

3. Experimental Results

3.1. Synchronization of Lasers without Optical Feedback

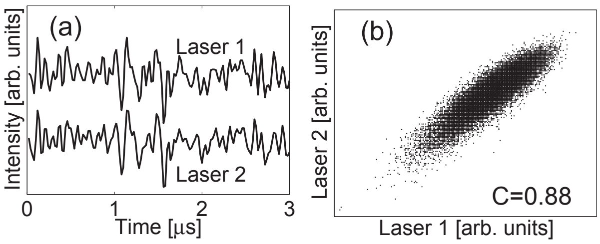

Figure 2: Example of synchronization with a high correlation value. (a) Waveforms of the two lasers and (b) their correlation plot. The injection currents is $J = 1.8J_{th}$ and the relaxation frequencies are about ~ 4 GHz. The wavelengths of the two lasers without injections are matched at $\lambda = 1554.28$ nm.

An example of waveforms of the two DFB lasers is shown in Fig. 2 (a). We can see that the waveforms are similar to each other. The correlation plot is represented in Fig. 2 (b) so as to recognize the quality of synchronization visually. In order to measure the quality quantitatively, we used a cross correlation coefficient C of the temporal waveforms between two lasers: i.e.,

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

where $\langle\rangle_t$ means the time average, $I_{1,2}(t)$ are the intensity time series of the two lasers, $\bar{I}_{1,2}$ are their mean values, and $\sigma_{1,2}$ are their standard deviations. In the case of Fig. 2 (b), the cross correlation coefficient C is 0.88.

The intensity of injected ASE light is measured by a power meter connected to the output monitor of the EDFA. Figure 3 shows that the cross correlation C as a function of the light intensity at the EDFA connected to Laser 2 when the intensity for Laser 1 is fixed. There is a light intensity of Laser 2 that maximize the correlation values. Here, intensity values of injected ASE light are determined as that measured at the output monitor of EDFA connected to Laser 1 and the light intensity for Laser 2 is adjusted so that the maximum cross correlations are achieved. This is the key point to acquire good synchronization. The peak wavelength of a laser becomes long as injected ASE light increases. The shapes of the optical spectra for the two lasers are coincident with each other except for parallel displacement in a vertical direction at the maximum correlation as shown in the lower right inset of Fig. 3. On the hand, they are different if C does not reach the maximum value and an example of spectra is shown in the upper left inset of Fig. 3.

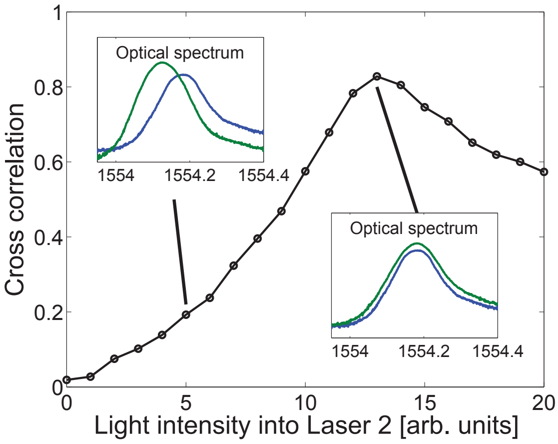

Figure 3: Dependence of the cross correlations C on the intensity of light injected into Laser 2. The insets show the optical spectra for two lasers at two light intensity values, 5 and 13. Blue and green curves represent optical spectra of Laser 1 and 2, respectively.

Figure 4 shows the dependence of the correlation coefficients C on the intensity of ASE light for some injection currents to the lasers. In the case of $J = 1.8J_{th}$, $J = 2.1J_{th}$, and $J = 2.5J_{th}$, as the injected light becomes strong, the correlation values increase, then decrease, and increase again. In other words, there are local maxima in the ranges of weak injection light for relatively large injection currents. The peaks of local maxima move to left and their heights decrease as the injection light becomes weak. Finally, we can not see local maximum for small injection light intensities such

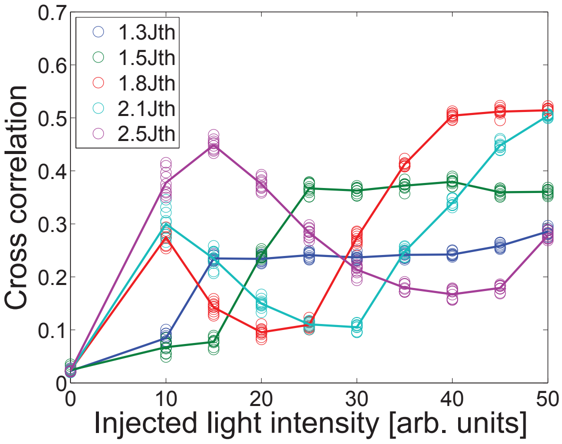

Figure 4: Cross correlation dependence on the intensities of injected ASE light for same injection currents to the lasers.

as $1.3J_{th}$ and $1.5J_{th}$ in Fig. 4. The correlation values C increase up to saturation values as the injected light becomes strong. We cannot investigate so large intensities of injection light that C approaches saturation values for $J = 2.1J_{th}$ and $J = 2.5J_{th}$ due to the limitation of experimental apparatuses. In general, there is the tendency that good synchronization is observed for large injection currents.

Next, we investigated the characteristics of the synchronization when the bandwidth of injected ASE light is limited by a bandpass filter. Figure 5 shows the cross correlations C versus the injected intensities for some bandwidths. The saturation values of C become large as the bandwidths of injected light become narrow. The rises of C up to the saturation values begin from weaker injection light as their bandwidths become narrower. We can say that the higher quality of synchronization can be achieved with narrower bandwidths of injected ASE light. The energy density of narrower band light is higher if the total intensity is the same. In addition, it is conjectured that part of injected light around the wavelength of a laser strongly affects the behavior of the laser. These can be the explanation of the early rising of C observed in our experiments. We can also see that the heights of local maxima in the weak injection light region become low as the bandwidth becomes narrow.

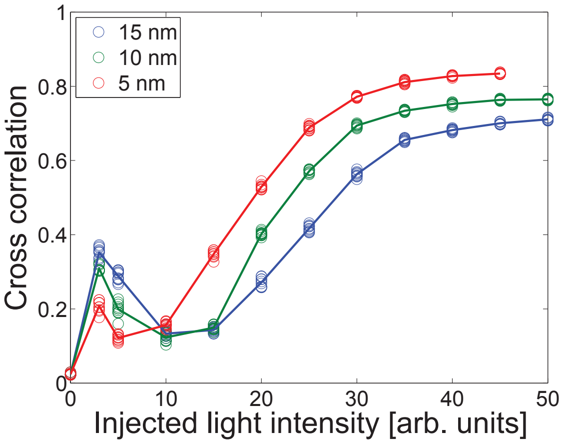

Figure 5: Cross correlations versus the intensities of injected ASE light for some bandwidths. The center of the passed bands is 1556 nm. The injection current is $J = 2.0J_{th}$ and the wavelength of lasers without injection is 1554.33 nm.

3.2. Synchronization of Lasers with Optical Feedback

We used DFB lasers embedded in PIC, which are monolithically integrated with some optical components such as semiconductor optical amplifiers (SOAs), and passive waveguides. At an end of waveguide, there is a high-reflected (HR) coating at which light can reflect. By injecting the currents to the SOAs, the light emitted from a DFB laser can pass through SOAs, reach a HR coating, and return back into the DFB laser. With appropriate amount of currents to a DFB laser and SOAs, the behaviors of the DFB laser become unstable and the intensity of emitted light behaves chaotically.

Here, we injected ASE light into such DFB lasers. Figure 6 (a) shows an example of waveforms of chaotic laser injected by common ASE light. The two waveforms are similar to each other. The correlation plot is shown in Fig. 6 (b) and the cross correlation coefficient is $C = 0.81$.

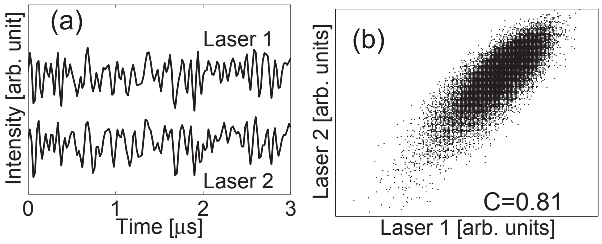

Figure 6: Example of synchronized response with high correlation ($C = 0.81$). (a) Waveforms of two lasers and (b) correlation plot.

Figure 7 shows the cross correlation as the function of injected ASE light. The cross correlations increase as the drive ASE light increases.

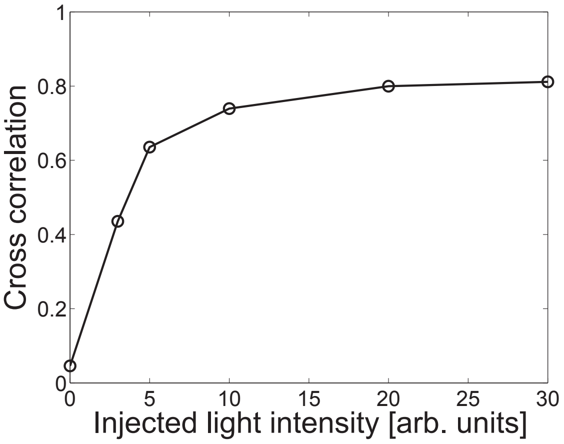

Figure 7: Cross correlation dependence on the intensity of driving ASE light with optical feedback. The injection current is $J \sim 1.1J_{th}$ and the wavelength is 1554.085 nm.

4. Summary

We observed the synchronization of two semiconductor lasers by the injection of common SLD light. In the absence of optical feedback, we observed local maxima of cross-correlation values in the region of weak injected ASE light and the cross-correlation values of the local maxima increase as injection currents to lasers increase. In addition, by the extrapolation estimation of strong enough injected light intensities, larger cross correlation values can be obtained for larger injection currents. We can also see that good synchronization can be realized for narrow bandwidths of ASE light. With optical feedback, we observed good synchronizations for large injection intensities.

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