EXPERIMENTAL OBSERVATION OF SYNCHRONIZATION AND ANTI-SYNCHRONIZATION OF CHAOTIC LOW-FREQUENCY-FLUCTUATIONS IN EXTERNAL CAVITY SEMICONDUCTOR LASERS

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Experimental investigations of synchronization and anti-synchronization of optically coupled semiconductor lasers with external cavities are presented. Both lasers show chaotic low-frequency intensity fluctuations that are (anti-) synchronized due to optical coupling by light injection. For uni-directional coupling response lasers with and without external cavity are considered. In the case of bi-directional coupling synchronized fluctuations are observed even without external mirrors.

1. Introduction

During the last decade synchronization of chaotic systems has been explored very intensively by many researchers in various fields ranging from physics, mathematics to engineering, where for the latter the main motivation has been potential practical applications in communication systems [Pecora & Carroll, 1990; Kocarev & Parlitz, 1995; Parlitz et al., 1996; Kennedy & Ogorzalek, 1997; Schuster, 1999]. Many modern communication devices are opto-electronic or all optical. Therefore, chaotic laser systems showing synchronization phenomena are of special interest and have been investigated theoretically as well as experimentally during the last years. Synchronization of chaotic lasers was first observed with Nd:YAG and CO₂ lasers [Roy & Thornburg, 1994; Sugawara et al., 1994; Colet & Roy, 1994]. Recently, synchronization of chaotic erbium-doped fiber ring lasers [VanWiggeren & Roy, 1998a; Abarbanel et al., 1998; VanWiggeren & Roy, 1998b] and semiconductor lasers (SL) [Mirasso et al., 1996; Annovazzi-Lodi et al., 1997; Ahlers et al., 1999; Sivaprakasam & Shore, 1999; Takiguchi et al., 1999] has been demonstrated experimentally and numerically. Since they are compact and can easily be modulated [Agrawal & Dutta, 1993] chaotic semiconductor lasers are of particular importance for potential applications in communication systems. Chaos in semiconductor lasers arises in different ways: due to an external cavity (optical feedback) or due to electro-optical feedback where the pump current is modulated by the emitted light intensity. A communication scheme based on synchronization of chaotic laser diodes with electro-optical feedback was implemented experimentally by Goedgebuer et al. [1998]. Recently, Chen and Liu simulated successfully information transmission using optical feedback [Chen & Liu, 2000]. External cavity semiconductor lasers (ECSLs) have been a subject of extensive research during the last 15 years because of the importance of optical feedback phenomena in technical
applications like optical data storage or optical fiber communications [Fischer et al., 1996]. In most of these cases, the effects of optical feedback are to be avoided. A typical effect due to feedback is low frequency fluctuations (LFF), which can be observed for moderate feedback and low pump current. This phenomenon has attracted considerable interest during the last few years. Numerical simulations based on a deterministic model [Ahlers et al., 1999] indicate that LFF dynamics is governed by a very high-dimensional chaotic attractor and are thus very difficult to distinguish from a stochastic signal, a feature that makes them an interesting candidate for an optical encryption system.

Synchronization of ECSLs has previously been studied numerically using different coupling schemes [Mirasso et al., 1996; Annovazzi-Lodi et al., 1997; Ahlers et al., 1999]. Only recently, two groups succeeded in achieving synchronization of LFFs experimentally [Sivaprakasam & Shore, 1999; Takiguchi et al., 1999]. In this letter we show that not only synchronization but also anti-synchronization can be achieved by means of a uni-directional optical coupling. Switching between both types of synchronization is possible, for example, by changing slightly the pump current of the drive system. In this way, such a configuration can in principle be used for chaos shift keying [Parlitz et al., 1992]. Furthermore, we demonstrate experimentally that with bi-directional coupling both lasers show synchronized LFFs without external mirrors.

2. Uni-Directional Coupling

The experimental set-up is shown in Fig. 1 where the optical diode (Faraday Isolator, Optics For Research IO-635-HP) is used only for uni-directional coupling. The fluctuating intensities of the semiconductor lasers (Mitsubishi ML 1412R) are measured with photo detectors, amplified (and inverted) and sampled with 1 Giga Sample per second using a digital oscilloscope (LeCroy LC 574AM) that is also used for display and further processing of the data. As pointed out in [Ahlers et al., 1999] at the response laser the light reflected from the mirror of the external cavity can be “replaced” by the light injected from the drive laser, i.e. the response laser can also synchronize without possessing an external cavity. In the following we shall consider both cases.

2.1. Response laser with external cavity

Intensity fluctuations of drive and response laser without coupling are shown in Fig. 2. If the coupling is switched on one may either observe synchronization (Fig. 3) or anti-synchronization (Fig. 4) depending on the pump currents and temperatures of both lasers. To compensate the phase shift between the signals from both photo detectors due to the propagation of light from drive to response the detectors have been connected with the digital oscilloscope by cables of suitable length.

Fig. 1. Experimental setup of two uni-directionally coupled external cavity semiconductor lasers.
Fig. 2. Low frequency fluctuations of the light intensities of drive (1, red) and response (2, blue) laser without coupling. Both signals are inverted. Horizontal scale: 0.2 $\mu$s/unit; Vertical scales: 20 mV/unit.

Fig. 3. Synchronization of uni-directionally coupled external cavity lasers (compare Fig. 2). (a) Inverted intensities of drive (1, red) and response (2, blue) versus time. Horizontal scale: 0.1 $\mu$s/unit; Vertical scales: 20 mV/unit (red) and 50 mV/unit (blue). (b) Inverted intensity of drive versus inverted intensity of response.

2.2. **Response laser without external cavity**

If the mirror of the external cavity of the response system is removed and only the light intensity of the drive is injected into the response laser, both lasers may still synchronize [Ahlers et al., 1999] as shown in Fig. 5. Again anti-synchronization may be observed by detuning the temperature (i.e. the wavelength) or the pump current (Fig. 6). For
transmitting a binary message one may want to switch between synchronization and anti-synchronization of the response laser. The efficiency of such a method would be limited by the length of the synchronization transient. Therefore we have used a periodic rectangular modulation of the drive current with 200 KHz in order to simulate a binary message. Figure 7 shows the intensities of drive and response and a transition from synchronization to anti-synchronization. The current modulation changes slightly the intensity of the driving laser which is clearly visible in the figure due to
Fig. 6. Anti-synchronization of uni-directionally coupled semiconductor lasers where only the drive laser possesses an external cavity (compare with Fig. 5). (a) Inverted intensities of drive (1, red) and response (2, blue) versus time. Horizontal scale: 0.1 μs/unit; Vertical scales: 20 mV/unit (red) and 50 mV/unit (blue). (b) Inverted intensity of drive versus inverted intensity of response.

Fig. 7. Switching between synchronization and anti-synchronization by changing the pump current of the drive (drive (1, red) and response (2, blue)). Horizontal scale: 0.2 μs/unit; Vertical scales: 36 mV/unit (red) and 100 mV/unit (blue).

AC-coupling of the signal from the photo detectors. The synchronization transient takes about 0.6 μs. The clear visibility of the modulation in the transmitter light intensity and the relatively long synchronization transient suggest that further improvements are necessary before this coupled system may be considered as a useful building block of an optical communication system.

3. Bi-Directional Coupling

When removing the optical diode in Fig. 1 we obtain a bi-directionally coupled system of
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Fig. 8. Synchronization of bi-directionally coupled semiconductor lasers without external mirrors. Horizontal scale: 0.2 μs/unit; Vertical scales: 27.5 mV/unit (red) and 62 mV/unit (blue).

...semiconductor lasers. Again synchronization and anti-synchronization may be observed with one or both lasers possessing an external cavity. However, even without any external mirrors such a pair of semiconductor lasers may generate nontrivial dynamics. Figure 8 shows as an example chaotic intensity oscillations which are quite similar to the synchronized low-frequency-fluctuations presented in the previous section. In contrast to the signal from a single (driving) laser with external cavity the signal-to-noise ratio is much better with the bi-directionally coupled pair. The possibility of generating (hyper-) chaotic dynamics using optical coupling and without external mirrors also warrants further investigations.

4. Conclusion

In this letter we presented experimental observations of (anti-)synchronization of uni-directionally and bi-directionally coupled semiconductor lasers with and without external cavities. In the unidirectional case it was shown that binary messages can in principle be transmitted by switching between synchronization and anti-synchronization. However, to apply this mode of communication practically shorter transient times are necessary and for cryptographic purposes the switching should not affect physical variables (e.g. amplitudes or (light) frequencies) whose changes could be detected quite easily. Using anti-synchronization one may generate not only drop-outs of the intensity (as with ordinary LFF) but also short pulses of high intensity. The bi-directional optical coupling offers new ways for generating chaotic (LFF) intensity oscillations that may also be useful as building blocks in chaos-based optical communication systems or (e.g. in combination with chaos control) for generating pulses of special shapes.

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References


