Observation of the synchronization of chaos in mutually injected vertical-cavity surface-emitting semiconductor lasers

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Synchronization of chaotic oscillations was observed in mutually injected vertical-cavity surface-emitting lasers (VCSELs) in a low-frequency fluctuation regime. In the experiments, only one of the two polarization modes (x mode) showed synchronized oscillations, and the other polarization components (y mode) were synchronized as a result of the effect of anticorrelated oscillations that is a characteristic feature of VCSELs. © 2003 Optical Society of America

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Despite high reflectivity (more than 99%) of their facets, vertical-cavity surface-emitting lasers (VCSELs) are sensitive to optical injection or optical feedback. In fact, nonlinear dynamics similar to those for edge-emitting semiconductor lasers have been observed experimentally. The output from a VCSEL is usually linearly polarized along one of the two orthogonal directions associated with crystalline or stress orientation. Some VCSELs display polarization and transverse mode instabilities, which degrade the performance of the laser oscillations. The polarization mode changes when the VCSEL is subjected to optical injection either by optical feedback or by external optical injection from a different laser. It is also shown that optical injection can control the polarization mode.

One of the important applications of chaotic lasers is secure data transmissions and communications based on synchronization of chaos. Synchronization of chaos in edge-emitting semiconductor lasers has already been studied experimentally and theoretically. Recently, a few studies of synchronization of chaos in VCSELs have been published, but we know of no experimental result that has been reported yet. Because a VCSEL has a complicated polarization dynamics, it is not easy to synchronize chaos experimentally. In this Letter we demonstrate for the first time to our knowledge the experimental observation of synchronization of chaos in mutually coupled VCSELs in a low-frequency fluctuation (LFF) regime.

The VCSELs (AXT Model VY-TI11-4FO1 VCSELs) used in the experiments oscillated at a wavelength of 780 nm and had a maximum optical power of 10 mW. The lasers oscillated at the y-polarization mode just above threshold (y is the direction along the optical axis of a laser material). The x-polarization mode is defined here as the counterpart oscillation of the y-polarization mode perpendicular to the x component. With the increase of the injection current, the output power of the x-polarization mode increased and had a power that was comparable with that of the y-polarization mode in our experiments, although the x-polarization mode always had lower power than the y-polarization mode. The two lasers were mutually coupled through a neutral-density filter to control the injection ratios. Thus one VCSEL (VCSEL1) was injected by the other VCSEL (VCSEL2) and VCSEL2 was also injected by VCSEL1. The bias injection currents of the two lasers were controlled by stabilized current source drivers, and the laser temperature was stabilized at 25.8 °C by automatic temperature control circuits. The two lasers used in our experiments had similar values of the device parameters. In spite of the similar device parameters, each VCSEL showed quite different oscillation characteristics for the threshold injection current and the light-injection current (L-I) characteristics for both x- and y-polarization outputs.

The free-running threshold currents of VCSEL1 and VCSEL2 were 6.2 and 6.4 mA, respectively, at that temperature. The injection currents for VCSEL1 and VCSEL2 were biased at 7.2 mA (1.16Ith, where Ith is the laser threshold current) and 7.7 mA (1.20Ith), respectively. At the bias injection current, VCSEL1 showed low output power of the x-polarization mode and oscillated almost always in the y-polarization mode only. Comparable output powers for the y- and x-polarization modes were observed in VCSEL2. Under these conditions the lasers oscillated at their lower-order spatial modes (LP01 and LP11 modes). Each spatial mode was stable at solitary oscillation. The two lasers were separated in space by 120 cm. Therefore the coupling time of light between the two lasers was τ = 4 ns. The outputs from the two lasers were detected by a high-speed photodetector (New Focus 1537M-LF; bandwidth, 6.0 GHz). Chaotic waveforms were analyzed by a rf spectrum analyzer (HP 8595E; bandwidth, 6.5 GHz) and a fast digital oscilloscope (HP 54845A; bandwidth, 1.5 GHz). Also, the optical outputs were analyzed by an optical spectrum analyzer (Advantest Q8344A; maximum resolution, 0.05 nm), a wavelength meter (Advantest QT8325; maximum resolution, 0.001 nm), and a Fabry–Perot spectrometer (free spectral range, 10 GHz).

Figure 1 shows an example of the synchronization of chaotic oscillations in a LFF regime. Figure 1(a) shows time series of the x-polarization components for the two laser outputs. As discussed below, the wavelengths of the x-polarization modes were locked to each...
other under mutual optical injection, whereas the laser oscillations of the $y$ components had different wavelengths. The time duration of each step in the power recovery process of LFFs was coincident with the round-trip time $2t$ of light in the mutual optical injection system. We can see synchronized power dropouts in the waveforms of the $x$ components. It is not clear from the figure, but the time offsets between the two signals were not compensated for. In this figure, VCSEL1 was a leader of VCSEL2 and the time lag between the waveforms was 4 ns, which was equal to the coupling time $t$ of light between the two lasers.

Synchronized waveforms for the $y$ components are shown in Fig. 1(b). But the time series were obtained at a different time from those in Fig. 1(a). We note that the $y$-polarization mode of each VCSEL always oscillated out of phase with the $x$-polarization component. In general, mode competition between the two orthogonal polarization components in VCSELs gives rise to anticorrelated oscillations between the $x$- and $y$-polarization outputs in unstable operation. In Fig. 1(b), VCSEL1 was also a leader laser, and the time delay between the two waveforms was equal to the coupling time of 4 ns. Although the two waveforms in Fig. 1(b) were synchronized with each other, we cannot see clear power dropouts and stepwise power recoveries in their waveforms. As discussed below, the synchronization observed in the LFF regime originated intrinsically from the synchronization in the $x$-polarization components. Therefore the synchronization of the $y$ components was considered to be induced by anticorrelated oscillations to the $x$ components.

After compensating for the time lag, we calculated the correlation plot between the two waveforms. Figure 2 shows such plots. The calculated correlation coefficient of the $x$-polarization mode was 0.866, and that of the $y$-polarization mode was 0.633. Better correlation was achieved for the $x$-polarization components because the two lasers were basically synchronized in the $x$-polarization modes.

Figure 3 shows the optical spectra at solitary and mutually coupled oscillations observed by the optical spectrum analyzer. Each peak spectral power was normalized to the total oscillation intensity. The upper and lower traces in Fig. 3(a) are the spectra for the $x$-polarization components at solitary and optically coupled oscillations, respectively. These spectra correspond to the laser oscillations in Fig. 1. Before optical coupling, VCSEL1 has a very low power, but it showed significant power after the optical injection. The change of the optical power in VCSEL2, however, is slight in spite of the mutual optical coupling. The frequency difference between

![Fig. 1. Time series of laser outputs at synchronization: (a) $x$-polarization mode, (b) $y$-polarization mode.](image)

![Fig. 2. Correlation plots of the laser outputs for (a) Fig. 1(a) and (b) Fig. 1(b).](image)

![Fig. 3. Optical spectra of laser oscillations for (a) $x$- and (b) $y$-polarization modes. The conditions are the same as those for Fig. 1. Solid curves, spectra for VCSEL1; dotted curves, spectra for VCSEL2.](image)
the two lasers at solitary oscillation was $-14.3$ GHz (the difference is defined by $\Delta f = f_1 - f_2$, where $f_1$ and $f_2$ are the frequencies of VCSEL1 and VCSEL2, respectively.) The wavelengths of the two lasers were shifted by mutual optical injection. After optical coupling, the main oscillation wavelengths of the $x$-polarization components coincided at 779.02 nm. By considering the results shown in Fig. 1 together with the spectra observed here, we concluded that the $x$-polarization mode of VCSEL2 was locked to that of VCSEL1 and that the two lasers were synchronized at that wavelength.

Figure 3(b) shows the spectra for the $y$-polarization components at solitary and mutually coupled oscillations. The spectra were observed under the same conditions as for those in Fig. 3(a). The $y$ components both before and after optical coupling had significant optical powers. By optical injection, the optical power of VCSEL2 increased, whereas that of VCSEL1 decreased. However, the differences were slight. The important results were that the oscillation frequencies of the two VCSELs differed not only at the solitary oscillations but also for the mutually coupled conditions. The frequency difference between the two lasers was originally 6.9 GHz, and it increased to $-27.2$ GHz after the mutual optical coupling. Therefore each laser at the $y$-polarization mode was not injection locked by the optical coupling. Only antiphase oscillations to the $x$-polarization modes showed.

Although the results were not shown here, we examined the optical spectra at synchronization, using a Fabry–Perot spectrometer. In the absence of optical coupling, we could recognize significant spectral peaks in the two laser outputs, and they oscillated while they maintained their coherence. However, the coherence was completely destroyed at LFF oscillations after mutual optical injection. This result is quite consistent with those for previously observed LFFs in edge-emitting semiconductor lasers. The rf spectrum of each polarization mode was investigated by a rf spectrum analyzer. A typical frequency and its higher harmonics that were due to LFFs were observed at the optical coupling conditions. The observed dominant frequency was coincident with that which corresponded to the round-trip time of light between the two lasers, i.e., $f = 1/2\tau$.

We have experimentally demonstrated the synchronization of chaotic oscillation in mutually injected VCSELs in a LFF regime. In synchronization of chaos in VCSELs the polarization modes play an important role. It is well known that the two orthogonal polarization components in VCSELs show out-of-phase oscillations during dynamic operation.\textsuperscript{8,9} We have examined various cases of chaos synchronization in a LFF regime in mutually injected VCSELs. We have not shown the results here, but, for example, we have observed synchronization at $y$-polarization modes and the counterpart modes ($x$-polarization mode) synchronized with each other as a result of the antiphase correlations. Another example was almost perfect synchronization both for $x$- and for $y$-polarization modes. In the latter case the respective polarization components were both injection locked. The method of synchronization depends on the parameter conditions, such as bias injection current, and the experimental configurations. They also determine a leading (master) or lagging (slave) laser in the synchronization system. We have demonstrated synchronization of chaos in VCSELs for the first time to our knowledge; however, the synchronization was limited to mutually coupled modes in LFF regime. We can also expect synchronization of chaos in unidirectionally coupled VCSELs at high-speed responses of the order of the laser relaxation oscillations (gigahertz oscillations) in the same manner as that in edge-emitting semiconductor lasers.

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References