Periodic entrainment of power dropouts in mutually coupled semiconductor lasers

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We examine the effect of current modulation in the irregular dropout dynamics exhibited by two mutually coupled semiconductor lasers. Our experimental results show that a weak periodic modulation in the injection current of one of the lasers entrains the power dropouts in a very efficient way. It is also observed that the laser with the highest frequency leads the dynamics independent of which laser is modulated. As a result, the entrainment is anticipative when modulation is applied to the laser with lowest frequency. Numerical simulations of a model based on delay-coupled rate equations successfully reproduce the behavior observed. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1533837]

Synchronization of coupled lasers has emerged in recent years as the basic mechanism underlying applications as diverse as high-power coherent emission by laser arrays,[1] quantum-noise reduction via twin-beam generation,[2] and information transmission in chaotic communication systems.[3] In the last, information is encoded in the chaotic carrier generated by an emitter laser and decoded by a receiver laser to which the emitter is synchronized. Most of the schemes designed to that end are based on *unidirectional* coupling, in which the light emitted by one laser is partially injected into the other laser. However, some attention has also been directed toward the case of *bidirectional* coupling, in which the two lasers equally affect one another through mutual injection.[4] Recent investigations of this scheme have shown that mutual coupling destabilizes the otherwise steady-state operation of the lasers by inducing sudden power dropouts that occur irregularly during the time evolution of the synchronized lasers at frequencies of the order of megahertz.[5,6] The mechanism that leads to this instability is believed to be similar to that involved in the occurrence of low frequency fluctuations in semiconductor lasers subjected to optical feedback.[7] In this letter we show that the irregular power dropouts exhibited by two mutually coupled lasers can be entrained periodically in a very efficient way by adding small amplitude modulation to the injection current of one of the lasers.

Our experimental setup is shown schematically in Fig. 1. We use two index-guided AlGaInP semiconductor lasers (Roithner RLT6505G) with a nominal wavelength around 650 nm, whose injection current (temperature) is controlled within an accuracy of ± 0.1 mA ($\pm 0.01\,°$C). In the results presented here, we set the temperatures of the lasers to $T_1 = 18.15\,°$C and $T_2 = 22.25\,°$C, the solitary laser thresholds of which are $I_1^{\mathrm{th}} = 17.5$ mA and $I_2^{\mathrm{th}} = 17.3$ mA, respectively. The output of each laser is collimated by an antireflection-coated laser-diode objective, and injected into the other laser at a distance of 1.02 m, which corresponds to an external cavity of $\tau_c = 3.4$ ns. The reduction in threshold due to the feedback introduced by the facet of the opposite laser is 1.71% in laser 1 and 1.16% in laser 2. We note that these feedback strengths are not large enough to introduce any significant dynamical behavior in either laser when the other is turned off. A sinusoidal modulation is introduced into one of the lasers through an Agilent 33120A function generator.

In order to maximize the interaction between the mutually coupled lasers, we force them to operate at wavelengths as similar as possible by adjusting their input currents. For $I_1 = 17.8$ mA and $I_2 = 17.7$ mA the lasers have a similar optical spectrum, centered at $\lambda = 657.0$ nm. Under these conditions, the output intensities of both lasers exhibit synchronized power dropouts, as shown in Fig. 2(a), which displays

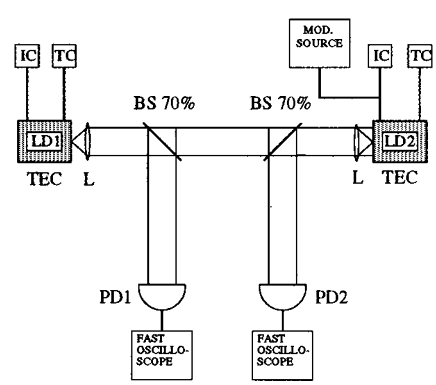

FIG. 1. Experimental setup: LD, laser diode; BS, beam splitter; TEC, laser diode mount; PD, photodiode; IC, injection current source; TC, temperature controller.

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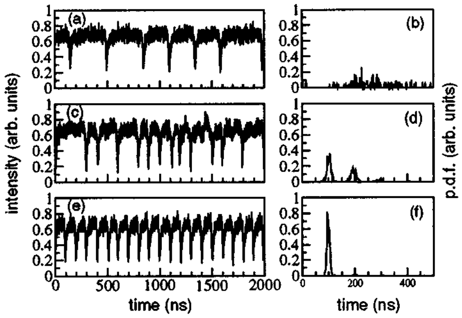

FIG. 2. Time evolution and the corresponding probability distribution function of the intensity dropouts for increasing values of modulation amplitude: 0 (a), (b), 0.23 (c), (d) and 0.30 mA (e), (f) respectively.

the intensity evolution of one of the lasers (the other one is basically identical). These dropouts are irregularly spaced over time, as can be seen in the probability distribution function of the time interval between consecutive dropouts, displayed in Fig. 2(b). When 10 MHz sinusoidal modulation is added to the injection current of one of the lasers, the dropouts start to become entrained toward the external periodic driving. For low modulation amplitudes the intensity dropouts occur at multiples of the modulation period [Figs. 2(c) and 2(d)], and if the amplitude is further increased we finally observe complete entrainment to the modulation period [Figs. 2(e) and 2(f)]. This entrainment occurs for a wide range of coupling strengths between the two lasers, provided that the coupling is large enough for synchronization to exist. We note that the levels of modulation amplitude required to reach this entrainment are low in comparison to the mean bias level of the injection current ($\sim$1.7%). This is in contrast, for instance, with the case of dropouts exhibited by a single laser subjected to optical feedback, for which the modulation required to get entrainment is so large that it substantially distorts the overall dynamics of the laser (see, for instance, Fig. 3 in Ref. 8). In our case, when the modulation amplitude becomes large enough the dropouts disappear, and the two lasers exhibit modulated output led by the laser that is subjected to the modulation. Entrainment is also observed for a wide range of modulation frequencies, larger than the mean dropout frequency of the laser without modulation, similar to what is found in the case of a single laser with feedback.[8]

Both with and without modulation, the dropouts of the two lasers are synchronized with a constant delay time approximately equal to the flight time between the lasers $\pm\tau_c$. For nonzero detuning (but small enough to maintain synchronization), the laser with higher frequency always leads the dynamics,[5] an effect which may be related to the asymmetric response of semiconductor lasers to injection. Figures 3(a) and 3(b) show intensity time traces of both lasers in the case of complete entrainment, when the leader laser is modulated. It can be seen that the dropouts occur earlier in the leader laser than in the laggard laser. In order to quantify this, Fig. 3(c) shows a synchronization plot of the two time series, with the intensity of the laggard laser advanced $\tau_c = 3.4$ ns.

A previous analysis of the chaos pass filtering properties of two mutually coupled lasers has shown that the leader and laggard roles are clearly different, with the leader synchronizing the laggard but not the other way around.[5] However,

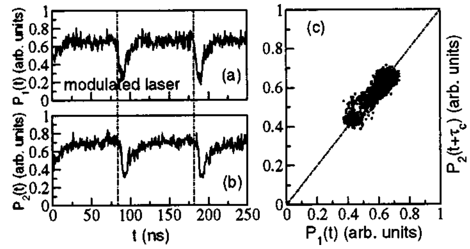

FIG. 3. Intensity time traces of the two lasers (a), (b) and delayed synchronization plot (c) for complete entrainment and when the laser with higher frequency is modulated.

we have observed that modulating the laggard instead of the leader does not affect the order of dropouts. Therefore, entrainment is transferred from the laggard to the leader in the form of *anticipated synchronization*.[9–11] This situation is displayed in Fig. 4, which shows how laser 1 (the one with higher frequency), even though it is not modulated, exhibits dropouts at the modulation period, anticipating the behavior of the modulated laser. We note that we observe a symmetric scenario by changing the sign of detuning between the two lasers (thus ruling out any systematic effect due to qualitative differences between them).

With the aim of reproducing the experimental observations, we have studied a phenomenological model which describes the behavior of the system by means of rate equations for complex slowly varying electrical fields $E_{1,2}$ and carriers $N_{1,2}$ of the two lasers:[12]

$$\frac{dE_{1,2}}{dt} = \frac{(1+i\alpha)}{2}[G_{1,2}-\gamma]E_{1,2} \pm i\Delta\omega E_{1,2} + \kappa e^{-i\Omega\tau_c}E_{2,1}(t-\tau_c), \tag{1}$$

$$\frac{dN_{1,2}}{dt} = \frac{I_{1,2}}{e} - \gamma_{e1,e2}N_{1,2} - G_{1,2}P_{1,2}(t), \tag{2}$$

where $G_{1,2}(t)=[g(N_{1,2}-N_0)]/[1+sP_{1,2}(t)]$ and the electric fields rotate at a symmetric reference frequency $\Omega = (\omega_1+\omega_2)/2$, with $\omega_{1,2}$ representing the free-running optical frequencies of the two lasers. The last term in Eq. (1) accounts for delayed injection between the lasers. The optical intensity (or number of photons inside the cavity) is given by $P_{1,2}(t)=|E_{1,2}(t)|^2$. We assume that the two lasers have an identical linewidth enhancement factor $\alpha=3.5$, differential gain $g=1.2\times10^{-8}$ ps^{-1}, gain saturation factor $s = 5\times10^{-7}$, and carrier number at transparency $N_0=1.25 \times 10^8$. Other parameters are assumed to differ slightly between the lasers, namely, cavity losses $\gamma_1=0.687$ ps^{-1} and $\gamma_2=0.496$ ps^{-1}, and carrier decay rates $\gamma_{e1}=0.601$ ns^{-1}

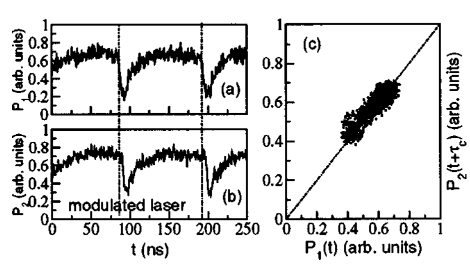

FIG. 4. The same as in Fig. 3, but with modulation of the laser with lower frequency.

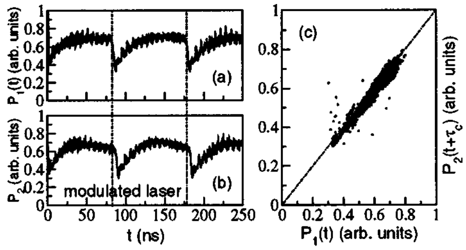

FIG. 5. Numerical results corresponding to the experimental time series in Fig. 4. The time series were filtered at 400 MHz in order to reproduce the bandwidth of the experimental detectors.

and $\gamma_{e2}=0.651$ ns^{-1}. These values were chosen in order to provide conditions similar to the experimental ones and reproduce the threshold currents ($I_{\mathrm{th1}}=17.3$ mA and $I_{\mathrm{th2}}=17.5$ mA). The time delay is $\tau_c=3.4$ ns, while κ is fitted to 20 ns^{-1}. The leader–laggard dynamics are obtained by introducing detuning between the laser frequencies $\Delta\omega=(\omega_1-\omega_2)/2=2$ GHz.

In the presence of harmonic driving, the injection current takes the form of $I_{1,2}=I_{b1,b2}+A_{1,2}\sin(2\pi t/T_m)$, where $A_{1,2}$ is the modulation amplitude and T_m is its period. In the numerical simulations, $I_{b1,b2}$ are adjusted to the respective threshold currents and T_m is 100 ns. The numerical results are in perfect agreement with the experimental data, and entrainment of the power dropouts is already observed when both the leader and the laggard are modulated with relatively small modulation amplitude. As an example, we show in Fig. 5 numerical results for $A_{1,2}=0.3$ mA that exhibit entrained dropouts when the laggard laser (the one with lower frequency) is modulated. Clearly, anticipated entrainment and a high degree of correlation are observed (upon advancing τ in the modulated time series), in very good agreement with the experiment. The same kind of entrainment, but retarded, is observed when modulating the leader laser.

In conclusion, two mutually coupled semiconductor lasers were experimentally and numerically analyzed when the injection current of one of the lasers was subjected to harmonic modulation. Entrainment of the coupling-induced power dropouts at the modulation period is obtained for relatively low modulation amplitudes, independent of whether the leader or the laggard laser is modulated. Therefore, anticipative entrainment is observed when the laggard laser is modulated.

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