Power dropout control by optical phase modulation in a chaotic semiconductor laser

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The effect of periodic phase modulation of light on a chaotic external-cavity semiconductor laser working in a regime of low-frequency fluctuations (LFFs) is studied numerically. It is observed that the phase modulation changes the time period between consecutive dropouts in the emitted laser intensity. A new variable $\Phi_m$ is defined as the phase of the laser’s LFFs, which increases in time with $2\pi$ after each power dropout event. The phase $\Phi_{PM}$ of the periodic phase modulator is unfolded on the real axis and increases linearly at a rate given by the modulating frequency. It is shown that the phase difference between the laser and the modulator $\Delta\Phi(t)=m\Phi_{L}(t)-n\Phi_{PM}(t)$, where $m$ and $n$ are integers, remains constant in time, leading to phase-synchronized states, for specific values of the modulating frequency and amplitude. © 2006 Optical Society of America

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1. INTRODUCTION

Semiconductor lasers are light sources extensively used in optical communications owing to several characteristics: compact size and ease of operation, optical power in a wide range from milliwatts to watts, the possibility of high-frequency modulation of the emitted light, and emission in the IR region of the spectrum where the absorption of the lasers’ light in optical fibers is minimal. However, because of their reduced cavity length, the optical linewidth is large enough to cause significant losses due to dispersion, especially in optical fibers. A technique known to minimize this undesirable effect is based on the use of optical feedback. When an optical reflector is placed in the path of the laser beam at a distance of a few centimeters in a configuration called an external-cavity semiconductor laser (ECSL), the active medium is constrained to lase at certain wavelengths that correspond to the external-cavity modes. The external-cavity modes are, in general, much narrower than the intrinsic longitudinal modes of the semiconductor laser.

Operated slightly above the lasing threshold, a typical ECSL with weak optical feedback runs into a regime temporarily unstable, manifested as a cyclic dropout of the output light intensity. The laser emission falls to almost zero at a rate of tens or hundreds of nanoseconds and then gradually returns to full power. The time intervals between these discontinuities are uncorrelated and depend on the parameters of the external cavity, as well as on the injection current. During the emission periods the output of the laser is not steady. The light intensity oscillates in time chaotically at a high frequency, however, with a much smaller amplitude compared with the average value of the emitted power. The reductions in the laser emission, also called low-frequency fluctuations (LFFs), are much slower compared with the fluctuations of the laser intensity at peak power. The complex laser dynamics that has two time scales is described by a high-dimensional chaos often called hyperchaos.

Control of the laser dynamics has been previously achieved either by modifying the coupling strength of the optical feedback or by modulating the injection current. Recently, an electro-optical modulator placed inside the external cavity led to the experimental observation of a variety of dynamical states, including periodic and chaotic states, which were induced by different modulating frequencies. Packets of regular pulses in the chaotic laser emission have been observed in the short-cavity regime and did not require an external perturbation.

Simple chaotic flows, which form a single-lobe attractor and for which a variable called phase can be well defined, associated with the circling in time of the trajectory about the fixed center, exhibit a tendency to phase synchronize with a low-amplitude external periodic signal properly applied to them. The external pacemaker is required to have a small amplitude and a frequency close to the dominant frequency of the oscillations in the chaotic system. A state of phase synchronization is reached when the difference between the phases of the two systems, i.e., the cha-
topic oscillator and the periodic pacer, remains constant in time. Phase synchronization has been observed in experiments with chaotic dc plasma tubes, chemical reactors, and electronic circuits. The attractor of chaotic lasers in the phase space is topologically more complex, and the usual definition of a variable that increases with \(2\pi\) is not applicable, since there is no unique fixed center of rotation. Nevertheless, a careful description of the laser output based on a Hilbert transform or on algorithms that sample the signal relative to its minima and maxima make possible the definition of a proper phase variable. Within this context, phase synchronization can be detected between chaotic lasers, as has been demonstrated in two coupled Nd:YAG lasers by Volodchenko et al. or in a Nd:YAG laser array by DoShazer et al.

In this paper the effect of periodic phase modulation of light on the rate of power dropouts is studied numerically in an ECSL working in the LFFs regime. The phase modulation of light induces a small time-varying delay in the total optical path inside the cavity, influencing the laser dynamics. It can be provided in an experimental situation by an electro-optical modulator or by a fast piezoelectric vibrating mirror. The laser intensity is a complicated time-varying waveform with high- and low-frequency oscillations corresponding to two time scales that differ by at least 1 order of magnitude. The attractor in the phase space is therefore far from being coherent, with a single lobe, and no phase variable can be properly defined. However, for the purpose of comparing the low-frequency oscillations of the output emission with the periodic phase modulator (PM), a new laser variable \(\Phi(t)\) is defined as the phase of the low-frequency fluctuations. This newly introduced phase increases with \(2\pi\) after each power dropout event. For convenience, the periodic modulating signal is taken as a sine wave. The phase of the modulator \(\Phi_{PM}(t)\) can be defined as a variable that increases linearly in time, at a rate given by the modulating frequency. This phase is unfolded on the real axis, and therefore it increases with \(2\pi\) after each cycle. It is observed that when the modulation is turned on, for some specific values of its frequency and amplitude, the time intervals between the dropouts in the laser emission tend to be regular. The two phase variables, of the laser system and of the modulator, increase in time at different rates as the laser responds in its own manner to the modulation. However, one can establish a correlation between these two phases by calculating their difference \(\Delta \Phi(t) = m\Phi(t) - n\Phi_{PM}(t)\), where \(m\) and \(n\) are integers. An \(m\)-to-\(n\) \((m:n)\) frequency locking is achieved between the laser power dropouts and the PM, when the phase difference stays constant in time. This procedure, of characterizing phase-locked states, has been previously used for correlating the cyclical signals recorded from different brain areas. The regularity induced by the modulator in the laser dynamics can also be assessed from the distribution of the time intervals between consecutive dropouts using Shanon's entropy.

The paper is organized as follows. The laser equations and the phases of LFFs and the modulator, as well as a coupling coefficient between these phases, are defined in Section 2. The synchronization of LFFs with the modulator is studied in Section 3, on the basis of Shannon's entropy and on the coupling coefficient. Also, the regions in the modulator parameter space \(\Omega_{PM-A}\), leading to synchronization of LFFs, are identified and mapped. At the end of Section 3, a linear stability analysis of the laser equations shows how the laser dynamics is affected by the PM.

## 2. MODEL FOR THE SEMICONDUCTOR LASER WITH PHASE MODULATION

### A. Laser Equations

A single-mode semiconductor laser and an optical reflector forming an external-cavity configuration are considered here. A PM is placed inside the cavity as shown in Fig. 1, while an optical isolator (OI) allows the propagation of light unidirectionally, from the modulator to the laser. The electric field inside the external cavity is the complex time-varying amplitude \(E(t)\), as introduced by Lang and Kobayashi. In our case, the laser equations, which include the phase of the modulator, are

\[
\frac{dE(t)}{dt} = (1 - i\alpha) \left[ G(t) - \frac{1}{\tau_p} \right] E(t) + \gamma E(t-\tau_r) \times \exp[i(\omega_0 \tau_r + A \sin(\Omega_{PM}))],
\]

(1)

\[
\frac{dN(t)}{dt} = \frac{I}{e} \cdot \frac{N(t) - G(t)|E(t)|^2}{\tau_n},
\]

(2)

\(\alpha\) is the linewidth enhancement factor, \(\tau_p\) is the photon lifetime decay rate, \(\gamma\) is the feedback coefficient, \(\tau_r\) is the external-cavity round-trip time, \(\omega_0\) is the optical frequency of the laser, \(N(t)\) is the carrier number density, \(I\) is the injection current, \(e\) is the unit charge, \(\tau_n\) is the carrier lifetime, \(g\) is the gain parameter, \(N_0\) is the carrier number at transparency, and \(s\) is the gain saturation coefficient. The exponential term \(\exp[iA \sin(\Omega_{PM})]\) of Eq. (1) accounts for the phase delay due to the PM. For the sake of simplicity, the spontaneous emission of the laser is neglected.

The retardation in the electric field introduced by the modulator is considered sinusoidal and given by

![Fig. 1. (Color online) Schematics of the external-cavity semiconductor laser configuration with a phase modulator (PM) and an unidirectional optical filter (OI).](image)
\[ \Delta \Phi_{PM} = A \sin \Omega_{PM} t, \]  

where \( A \) is the amplitude, measured in units of radians, and \( \Omega_{PM} \) is the driving frequency. The additional time delay introduced by the PM is small compared with the external-cavity round-trip time \( (\Delta t_{PM} << \tau_c) \), and therefore it is assumed in Eq. (1) that \( E(t-\tau_c-\Delta t_{PM}) = E(t-\tau_c) \). Also, the amplitude is taken such that \( A \equiv 0 \tau_c \). The effect of the PM on the electric field can be better understood by expanding the exponential term in series of Bessel functions:

\[
\exp[iA \sin(\Omega_{PM} t)] = J_0(A) + i \sum_{k=0}^{\infty} 2J_{2k+1}(A) \sin[(2k+1)\Omega_{PM} t] + \sum_{k=1}^{\infty} 2J_{2k}(A) \cos(2k\Omega_{PM} t). \]

Depending on the value for \( A \), the series can be approximated as follows. For \( A \ll 1 \), \( \exp[iA \sin(\Omega_{PM} t)] \approx J_0(A) + iJ_1(A) \sin(\Omega_{PM} t) \), and therefore the modulation has only an imaginary component, at the fundamental frequency. For \( A = 1 \), \( \exp[iA \sin(\Omega_{PM} t)] = J_0(A) + iJ_1(A) \sin(\Omega_{PM} t) + J_2(A) \cos(2\Omega_{PM} t) + iJ_3(A) \sin(3\Omega_{PM} t) \), and the modulation is mostly realized at the fundamental frequency \( \Omega_{PM} \) and its two first harmonics \( 2\Omega_{PM} \) and \( 3\Omega_{PM} \). For \( A \gg 1 \), the fundamental frequency \( \Omega_{PM} \) and its higher harmonics \( 2\Omega_{PM}, 3\Omega_{PM}, \ldots \) drive the laser. We will concentrate on the case when the modulating amplitude satisfies \( A = 1 \). For \( A \ll 1 \), there is no observable effect of the modulator on the laser dynamics.

B. Definition of Low-Frequency Fluctuations and Modulator Phases

The phase of the power dropout events in the laser intensity at a moment \( t \) is defined as

\[
\Phi_j(t) = \frac{2\pi t - t_j}{t_{j+1} - t_j} \pm 2\pi j, \quad \text{with } j = 1, 2, \ldots ,
\]

where \( t_j \) is the moment at which the \( j \)-th dropout event takes place. Between two consecutive dropouts this phase increases linearly at a constant rate, and therefore we can introduce for each interval \( \Delta t_j = t_{j+1} - t_j \) a single-event frequency \( \Omega_j(j) = 2\pi / \Delta t_j \). The phase \( \Phi_j(t) \) can then be written as \( \Phi_j(t) = \Omega_j(j)(t - t_j) + 2\pi j \). On the real axis \( \Phi_j(t) \) is a monotonically increasing piecewise function with different slopes for each interval \( \Delta t_j \). In the limit of large time, a mean dropout frequency can be defined as

\[
\langle \Omega_j \rangle = \lim_{t \to \infty} \frac{2\pi N}{t} = \frac{1}{N} \sum_j \Omega_j(j).
\]

The mean dropout period is therefore \( \langle \Delta t_j \rangle = 2\pi / \langle \Omega_j \rangle \), where \( N \) is the number of dropouts during the observation time \( t \). The following property can be found:

\[
\lim_{t \to \infty} \Phi_j(t) = \langle \Omega_j \rangle t.
\]

The phase of the modulator is determined by the modulating frequency \( \Omega_{PM} \):

\[
\Phi_{PM}(t) = \Omega_{PM}(t - t_k) + 2\pi k = \Omega_{PM} t, \]

where \( t_k \) is the moment at which the \( k \)-th cycle has been completed and \( 2\pi \Omega_{PM} \) is the period of the modulating signal. \( \Omega_{PM} \) is a parameter with a defined value, as opposed to the instantaneous frequency \( \Omega_j(j) \) of the laser's LFFs, which changes after each power dropout event.

The difference of the two phases in time is taken as

\[
\Delta \Phi(t) = m\Phi_j(t) - n\Phi_{PM}(t),
\]

where \( m, n \) are integers. In the limit of large \( t \),

\[
\lim_{t \to \infty} \Delta \Phi(t) = m\langle \Omega_j \rangle t - n\Omega_{PM}.
\]

Of interest here are the values of \( \Omega_{PM} \) for which \( |\Delta \Phi(t)| < \text{constant at all times} \). This condition can be fulfilled by one's requiring

\[
\frac{\Omega_{PM}}{\langle \Omega_j \rangle} = \frac{m}{n}.
\]

Equation (11) is usually employed to describe phase locking between two coupled periodic oscillators. We call this state an \( m:n \) phase-synchronized state between the laser power dropout events and the PM.

C. Characterization of the Coupling

In the simulations, the ratio between the two phases,

\[
r(t) = \frac{\Phi_{PM}(t)}{\Phi_j(t)},
\]

is calculated as the systems evolve in time, giving an evaluation of the instantaneous coupling. The degree of time correlation between the two phases and of the phase synchronization is indicated by the deviation in time of this ratio from a constant value \( m/n \).

An alternate method used to characterize the degree of synchronization between the laser and the modulator is based on Shannon's entropy.\textsuperscript{22} The entropy of the assembly is the sum of the probabilities of the states of the laser with the modulator, and \( 1 \) when \( S = S_{max} \), which corresponds to completely uncorrelated time intervals, or in our case to unsynchronized states of the laser with the modulator, and \( 1 \) when \( S = 0 \), which indicates the grouping of all the time intervals in a single bin. This latter case is characterized by a high level of synchronization between the laser and the modulator.
3. NUMERICAL RESULTS AND DISCUSSION

Equations (1) and (2) are solved using a fourth-order Runge–Kutta algorithm, with a Bogacki–Shampine step control method. The obtained time series of the laser intensity $E(t)$ are then low-pass filtered at a cutoff frequency of $3 \times 10^8$ rad/s. The first $10^4$ data points in each simulation are discarded, to avoid the initial transients. A cubic Hermite interpolation scheme is then employed to sample the resulting signal in order to find its minima.

The laser parameters used in the simulation are as follows: $\alpha=5$, $\tau_p=2$ ps, $\gamma=0.03$ ps$^{-1}$, $\tau_n=1$ ns, $\omega_0=1.2 \times 10^6$ G rad/s, $I = 15$ mA, $\gamma=15$ ns, $g=1.5 \times 10^{-8}$ ps$^{-1}$, $N_0 = 1.5 \times 10^8$, and $s=5 \times 10^{-7}$.

A typical output of the free-running ECSL is shown in Fig. 2(a). It can be easily seen how the power dropouts are spaced erratically in time as a result of the chaotic nature of the system. A significant change in the dynamics of the laser output intensity is observed when the PM is turned on. For an amplitude $A=1$ and frequency $\Omega_{PM}=1.97$ G rad/s, the succession of the dropouts is steady, with a length in time between consecutive events almost constant, as shown in Fig. 2(b). The distribution of these time intervals can be better visualized by depicting them on a histogram. A number of $N=87$ consecutive power dropout events are disposed in $M=11$ bins, as shown in Fig. 3. The effect of the modulation is obvious as most of the intervals have the same length in time. In this case the Shannon entropy is $S=0.92$, and the coefficient of synchronization increases sharply to $\sigma=0.70$.

It is important to notice that, although the modulator drives the laser emission at a high frequency $\Omega_{PM} = 1.97$ G rad/s, the effect on the laser dynamics is present at the low-frequency scale of the intensity oscillations ($=0.1–0.01$ G rad/s). Figure 4 shows the evolution in time of the modulator and laser phases represented with dashed–dotted and dashed curves, respectively, and their instantaneous ratio $r$ plotted with a continuous curve. After a transient period of time, the ratio of the two phases events are not exactly randomly distributed in time, and, to some low degree, they show a tendency of periodic repetition.

When the laser is modulated at the frequency and amplitude mentioned above ($A=1$ and $\Omega_{PM}=1.97$ G rad/s), most of the time intervals become restrained to the range between 0.78 and 1.03 $\times 10^{-2}$ μs. Their distribution has a pronounced peak in the histogram, as shown in Fig. 3(b). The effect of the modulation is obvious as most of the intervals have the same length in time. In this case the Shannon entropy is $S=0.92$, and the coefficient of synchronization increases sharply to $\sigma=0.70$.

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settles at \( r = 21 \), suggesting a locking of 21:1 between the frequency of the modulator and the average frequency of power dropouts.

When the modulating frequency \( \Omega_{\text{PM}} \) is varied between 1.0 and 2.52 G rad/s, keeping the amplitude constant \( A = 1 \), there is a resonant coupling with the laser dynamics only in a narrow range between 1.85 and 2.0 G rad/s, as can be seen in Fig. 5. The optimum control of LFFs, characterized by periodic power dropouts in the chaotic laser intensity, is attained in the interval \( \Omega_{\text{PM}} = 1.96 - 1.99 \) G rad/s. Here the LFFs are well synchronized with the external modulator, and the values for \( \sigma \) are high: \( \sigma \approx 0.6 \), with a peak \( \sigma = 0.7 \) at \( \Omega_{\text{PM}} = 1.97 \) G rad/s, as shown in Fig. 5(a). However, in a close vicinity as indicated by the arrows in Fig. 5, the laser is unstable and runs into regimes with different dynamics described as follows. In region (1), for \( \Omega_{\text{PM}} = 1.87 \) to 1.92 G rad/s, the chaotic emission is suppressed to a regime of oscillations with a low amplitude, which is \( \approx 25\% \) of the full laser intensity. This scenario is presented in Fig. 6(a). The output is eventually stabilized for \( \Omega_{\text{PM}} = 1.93 \) G rad/s, as shown in Fig. 6(b). In region (2), corresponding to \( \Omega_{\text{PM}} = 1.94 \) G rad/s, the emission becomes periodic with period-2 oscillations, as can be clearly seen in Fig. 6(c). Region (3), defined by \( \Omega_{\text{PM}} = 1.95 \) G rad/s, marks a regime of chaotic intermittency between LFFs and low-amplitude chaotic oscillations. The amplitude of these chaotic oscillations is much smaller than the maximum laser output. This regime is represented in Fig. 6(d).

The ratio of the modulator and laser phases, for different modulating frequencies and constant amplitude \( A = 1 \), is plotted in Fig. 5(b). As \( \Omega_{\text{PM}} \) is increased from 1 to 1.86 G rad/s, \( r \) increases from 17.2 to 58.0, suggesting that the laser phase \( \Phi_L \) lags behind the modulator phase \( \Phi_{\text{PM}} \). Within the region \( \Omega_{\text{PM}} = 1.87 \) to 1.95 G rad/s, the laser dynamics shows no LFFs, and \( r \) is not defined. Following this region, the laser enters a regime of steady LFFs, and the power dropout rate catches up with the modulator as \( r = 20.8 \) for \( \Omega_{\text{PM}} = 1.96 \) G rad/s. Then, as the modulator frequency reaches the value \( \Omega_{\text{PM}} = 2.52 \) G rad/s, \( r \) increases to \( r = 61 \).

The dynamical states of the phase-modulated laser are mapped for different values of the parameters \( \Omega_{\text{PM}} \) and \( A \). A grid with a resolution of 0.01 \( \times 0.1 \) is set in the zone bounded by \( 1.82 < \Omega_{\text{PM}} < 2.02 \) G rad/s and \( 0 < A < 1.6 \). The resolution is lowered to 0.033 \( \times 0.1 \) outside this rectangle. For each grid element the values of \( \sigma \) and \( r \) are calculated by one’s analyzing the laser dynamics in a time interval of 2 \( \mu \)s. The results for \( \sigma \) are shown in Fig. 7, and those for \( r \) are shown in Fig. 8. The local \( \sigma \) and \( r \) can be inferred in Figs. 7 and 8 from the correspondence between their val-
A ≥ 0.7. The synchronization region is shown in Fig. 7 with white and light gray, as σ ≥ 0.6 for these colors. It is interesting to notice that in Fig. 8, within the synchronization region marked with almost uniform gray color, r is limited to values only between 20 and 30. The present results demonstrate that a regime of steady LFFs can be obtained for a relatively wide range of modulator parameters Ω_{PM} and A.

The dynamics of the modulated ECSL can be studied by one's introducing the phase of the optical field and expressing the complex amplitude \( E(t) \) in terms of it, in Eqs. (1) and (2): \( \dot{E}(t) = E \exp[-i(\phi(t))], \) \( 27,28 \) with \( E(t) \) real. A system of nonlinear differential equations with the variables \( \dot{E}, \phi(t), \) and \( N(t) \) is obtained. \( 29 \) The stable points of this system can be found by one's looking for a stationary solution of the form \( \dot{E}_s, \phi(t) = (\omega_s - \omega_0)t, \) and \( N_s. \) The stable solution satisfies the following equations:

\[
\eta_s = - C \sin(\arctan \alpha + \eta_s + \omega_s \tau_s + \Phi_{PM}), \quad (14)
\]

\[
\Delta N_s = \frac{1}{2} \left[ 1 - \frac{2}{r_p} \cos(\eta_s + \omega_s \tau_s + \Phi_{PM}) \right], \quad (15)
\]

where \( \eta_s = (\omega_s - \omega_0) \tau_s, \) \( \Delta N_s = N_s - N_0, \) and \( C = \tau_s g (1 + \alpha^2). \) A stationary value \( \Phi_{PM} \) for the modulator phase is included in Eqs. (14) and (15). When the laser is not modulated, i.e., \( \Phi_{PM} = 0, \) the modes and antinodes, which are solutions of Eq. (15), are situated on the ellipse shown in Fig. 10(a), in the phase space \( \Delta N/N_0 \). \( 27,28 \) For reference, the solitary laser trajectory is also plotted in Fig. 10(a). The power dropouts in the laser intensity are the result of a collision between the attractor ruin of a stable mode and an antinode. \( 27 \) As an example, a region of the phase space that includes two pairs of external-cavity modes and their unstable saddles called antinodes, marked with (1) and (2), respectively, and corresponding to the solitary laser, is shown in Fig. 10(b). When the PM is turned on, its phase \( \Phi_{PM} \) varies in time sinusoidally, taking values between \( -A \) and \( A. \) It is interesting to see what happens to the stable solutions of Eqs. (14) and (15) when the additional term phase \( \Phi_{PM} \) is not zero. For \( \Phi_{PM} = A = -1, \) the modes and their antinodes are displaced in the same direction to new positions, marked with (3) and (4), respectively, corresponding to higher values for \( \eta_s. \) For \( \Phi_{PM} = A = 1, \) the modes and antinodes are displaced in the opposite direction with the same quantity, to the positions marked with (5) and (6), respectively. The effect of the modulator on the laser dynamics is therefore to push and pull the stable points of the system of differential equations about their fixed positions.

The PM is most effective when its period is comparable with the time taken by the laser trajectory to move between consecutive external-cavity modes. \( 30 \) For 23 modes (and antinodes) and an average time interval of about \( 1.5 \times 10^{-8} \) s between dropouts, as shown in Fig. 3(a), a rough estimate of the laser itinerary time between consecutive modes gives \( 1.5 \times 10^{-8}/11 = 1.3 \times 10^{-9} \) s, where we took a trajectory that visits approximately half of the total number of modes. The value is relatively close to the phase modulation period, when control of the power dropouts is achieved, which is \( \sim 3 \times 10^{-9} \) s. The trajectory of
the laser in the phase space, modulated at $\Omega_{PM} = 1.97$ G rad/s, is topologically the same as that of the solitary laser, as can be seen in Fig. 10(c). However, there are resonant frequencies that drive the chaotic laser into a periodic state. An example is shown in Fig. 10(d), where the laser trajectory follows only three external-cavity modes situated close to the maximum gain mode, for $\Omega_{PM} = 1.94$ G rad/s.

4. CONCLUSIONS

Numerical simulations show that the rate of power drop-out in the emission of an external-cavity semiconductor laser can be controlled with a phase modulator placed inside the cavity. The sinusoidal retardation introduced in the optical path inside the cavity by the modulator leads to steady LFFs in the laser light intensity. For some defined values of the modulating frequency, the light emission can also be stabilized from a regime of large-amplitude chaotic oscillations corresponding to LFFs to one of low-amplitude chaotic or even periodic oscillations. The degree of synchronization of the laser output with the modulator is determined in two different ways. The first one compares a newly defined laser variable, i.e., the phase of LFFs, with the phase of the modulator. The two phases are locked to a constant ratio $m:n$, where $m$ and $n$ are integers, when the laser synchronizes with the modulator. The second technique characterizes the irregularity of the time intervals between consecutive dropout events by calculating Shannon's entropy. The synchronization region in the parameter space of the modulator $\Omega_{PM}-A$ is mapped, and also the zones of stable, periodic, and low-amplitude chaotic emission are identified. A linear stability of the laser equations reveals that, when the modulator is turned on, the external-cavity modes and antimodes of the solitary laser are displaced about their initial position, at the frequency of the modulator. The dynamics of the laser can be controlled when the period of the modulating signal is comparable with the laser itinerancy time between consecutive external-cavity modes.

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REFERENCES


