Invited Paper

Optical-feedback-induced chaos and its control in semiconductor lasers

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ABSTRACT

In many applications such as optical data recording and fiber-optic communication systems, semiconductor lasers operate in the presence of external optical feedback (OFB). Such feedback is generally detrimental to the laser behavior, since it leads to higher intensity and frequency noise and increased laser linewidth. In this paper we will describe some of the effects of OFB on semiconductor lasers by simulation of the stochastic rate equations. Particular attention will be paid to the laser's transition to optical chaos. In addition, we will describe three techniques for avoiding this chaotic regime. The technique of high frequency injection, used in optical recording, can delay the onset of chaos till very high values of OFB. Experimental results are given and are in excellent agreement with the theory. A second technique called occasional proportional feedback can be used with some success to stabilize the chaotic output of semiconductor lasers. The final technique for controlling chaos consists of the optimization of various system and laser parameters so that the laser is least susceptible to OFB.

1. INTRODUCTION

The behavior of a semiconductor laser (SL) can be drastically altered when the laser is subjected to even a small amount of optical feedback (OFB).[1-16] Such feedback may arise from the reflection from an optical disk in a data storage system or from the end of a fiber in an optical fiber communication system. In can happen in virtually any application due to unwanted reflections from optical elements and detectors. In general, OFB can be either beneficial or detrimental to the operation of the laser. For example, weak feedback from an external mirror or grating can be used to force the laser to operate in a single longitudinal mode or wavelength.[1,2] The beneficial uses of feedback, however, require precise control over the external cavity characteristics. A minute variation in external cavity length or a vibration of the external mirror can ruin the beneficial effects of OFB. In a optical recording system, for example, where the disk serves as the external mirror, both the reflectivity and length of the external cavity fluctuate which usually causes the effect of OFB to be detrimental to laser performance.

There are several effects of OFB which adversely alter the behavior of SLs. Even for very small amounts of reflected light, the laser frequency may be shifted by an amount which depends on the phase of the feedback. Such frequency shifts are particularly degrading unless all optical elements are achromatized. At somewhat higher levels of OFB, the average laser power may change; in addition, the laser relaxation oscillations may become undamped causing the laser intensity to become destabilized. At this point the laser output is actually periodic at the relaxation oscillation frequency, on the order of 1 GHz. At still higher values of feedback, the laser may have significant oscillations at the frequency associated with the external cavity length. Depending on the magnitude of this frequency, the laser may actually exhibit chaotic behavior for certain levels of feedback. Such behavior is marked by a huge increase in low-frequency (< 1 GHz) intensity noise, sometimes accompanied by nearly complete dropouts of the laser power. The laser linewidth is also severely broadened in this regime.

Although it is possible to reduce such feedback to an acceptable level with the use of magneto-optical isolators, such an approach is often prohibitively expensive. In optical recording the effectiveness of a more "economical" isolator comprised of a polarizer and quarter-wave plate is reduced because of birefringence of the optical disk. Therefore a certain amount of OFB is inevitable and its effect on laser performance must be understood. This paper will describe the effects of OFB on SL behavior as well as describe some approaches for rendering the laser insensitive to OFB.

2. EFFECTS OF OPTICAL FEEDBACK

2.1 Rate equations with optical feedback

For levels of feedback when multiple reflections in the external cavity may be neglected, the laser behavior is described rather accurately by the so-called Lang and Kobayashi equations:[16,17]

$$\frac{dE}{dt} = \left[-i\,\frac{1}{2}\,\alpha G_N(N - N_s) + \frac{1}{2}\left(G - \frac{1}{\tau_p}\right)\right] E(t) + F_E(t) + \kappa E(t-\tau)\, e^{i\omega\tau} \tag{1}$$

$$\frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_e} - G|E(t)|^2 + F_N(t), \tag{2}$$

where E(t) is the slowly-varying complex amplitude of the intracavity optical field, τ_p is the photon lifetime, α is the linewidth-enhancement factor, N is the electron population, N_s is its steady-state value in the absence of feedback, I is the injection current, q is the magnitude of the electron charge, τ_e is the electron lifetime, and G is the net rate of stimulated emission assumed to vary linearly with the electron population as

$$G = G_N(N - N_0)(1 - \varepsilon S). \tag{3}$$

In Eq. (3), N_0 is the transparency value of N and the parameter G_N is related to the derivative of the optical gain with respect to the carrier density; S is the photon density, and ε is the nonlinear-gain parameter. The Langevin noise sources $F_E(t)$ and $F_N(t)$ represent the noise introduced by spontaneous emission and the shot noise due to carrier generation and recombination, respectively.

The last term in Eq. (1) is due to OFB and contains two parameters κ and τ. The feedback rate κ and the round-trip time τ are given by

$$\kappa = \frac{(1 - R_m)}{\tau_L}\left(\frac{\eta_c R_{ext}}{R_m}\right)^{1/2}, \quad \tau = \frac{2L_{ext}}{c}, \tag{4}$$

where η_c is the coupling efficiency (typically ~ 1-5%), R_m is the laser facet reflectivity, τ_L is the round-trip time in the laser cavity, R_{ext} is the reflectivity of the external mirror, and L_{ext} is the spacing between the laser and the external mirror. For the purpose of numerical simulations, we define F_{ext} as $F_{ext} = \eta_c R_{ext}$ so that F_{ext} represents the fraction of output power that reenters the laser cavity.

Equations (1) and (2), written for a laser oscillating in a predominantly single longitudinal mode, are easily extended to multi-longitudinal mode operation.[17] In this paper we solve these equations on computer using a fourth-order Runge-Kutta algorithm, the details of which as well as the parameter values can be found elsewhere.[17]

2.2 Regimes of feedback.

Optical feedback (OFB) affects the noise and dynamics of the laser in different ways, depending on the length of the external cavity and the strength of the feedback. It is common to divide these different effects into five regimes of feedback.[4] In regime I (−80 dB < F_{ext} < −70 dB) the laser linewidth is narrowed or broadened slightly depending on the feedback phase, $\omega\tau$. Regime II (−70 dB < F_{ext} < −45 dB) is characterized by mode hopping between external cavity modes. At still higher OFB, we find regime III, which admits the possibility of frequency locking to one of the external cavity modes, and regime IV, which is marked by severe line broadening (coherence collapse) and greatly increased intensity noise. The fifth regime (F_{ext} > −10 dB) is useful for stable line narrowing, but can normally be achieved only by anti-reflection coating the laser facet. The divisions between these five regimes are not hard and fast but depend on many parameters, perhaps the most important of which is the external cavity length.

A particularly useful tool for studying the effects of OFB over a wide range (regimes II-IV) is the bifurcation diagram.[15] The bifurcation diagram is constructed as follows: first, the noise sources in Eqs. (1) and (2) are turned off, so that we may distinguish between stochastic and deterministic noise; secondly, a time series is generated for each feedback level, and after the transients have died out, the carrier number N is recorded whenever the laser intensity crosses the solitary-laser value. Thus, no intersection in the diagram represents a constant power (fixed point) solution to the rate equations, whereas points of intersection imply periodicity, period doublings or chaos.

Figure 1 presents bifurcation diagrams for external cavity lengths L_{ext} in the range 10-100 cm, in order to show quantitatively the differences between long and short external cavities. The parameter $F_{ext}$is varied over a wide range (~ 40 dB) covering 10^{-6} to 5×10^{-3}. Figure 1(a) corresponds to a relatively long cavity (Lext = 100 cm). It shows a quasi-periodic route to chaos, in agreement with previous work [15]. However, for Lext = 30 cm [Fig 1(b)] the laser output becomes chaotic by following a period-doubling route. Two period-doubling bifurcations occurring at approximately $F_{ext} = 3.5\times10^{-6}$ and 6×10^{-6} are clearly evident, followed by full-blown chaos after $F_{ext} = 1.5\times10^{-5}$. While the two cases demonstrate two different routes to chaos, they share the common feature that chaotic behavior persists over a wide range of F_{ext} without stable windows of cw or periodic operation. That is, regimes III and IV are clearly separate. This is the defining feature of the long-cavity regime in which the external-cavity mode spacing $\nu_{ext} = 1/\tau$ exceeds the relaxation-oscillation frequency ν_R (about 800 MHz at 1.6-mW output power).

The qualitative behavior changes considerably in the short-cavity limit defined by the condition $\nu_{ext} > \nu_R$. For our laser this condition is satisfied for L_{ext} < 21 cm. Figure 1(c) shows the bifurcation diagram for the same laser, but with an external cavity length of 15 cm. There are two important quantitative differences as the external cavity becomes shorter: (i) the first occurrence of chaos happens at larger F_{ext} [18] and (ii) chaos is interrupted by multiple windows of stability as F_{ext} increases. Regimes III and IV are therefore intertwined for short external cavities. Furthermore, the stable windows become wider when L_{ext} decreases further. This is evident in Figure 1(d) which shows the bifurcation diagram for L_{ext} = 10 cm. The laser enters the first chaotic window through a period-doubling route at approximately $F_{ext} = 2\times10^{-5}$, but chaos gives way to a cw steady state when F_{ext} exceeds 6×10^{-5}. It

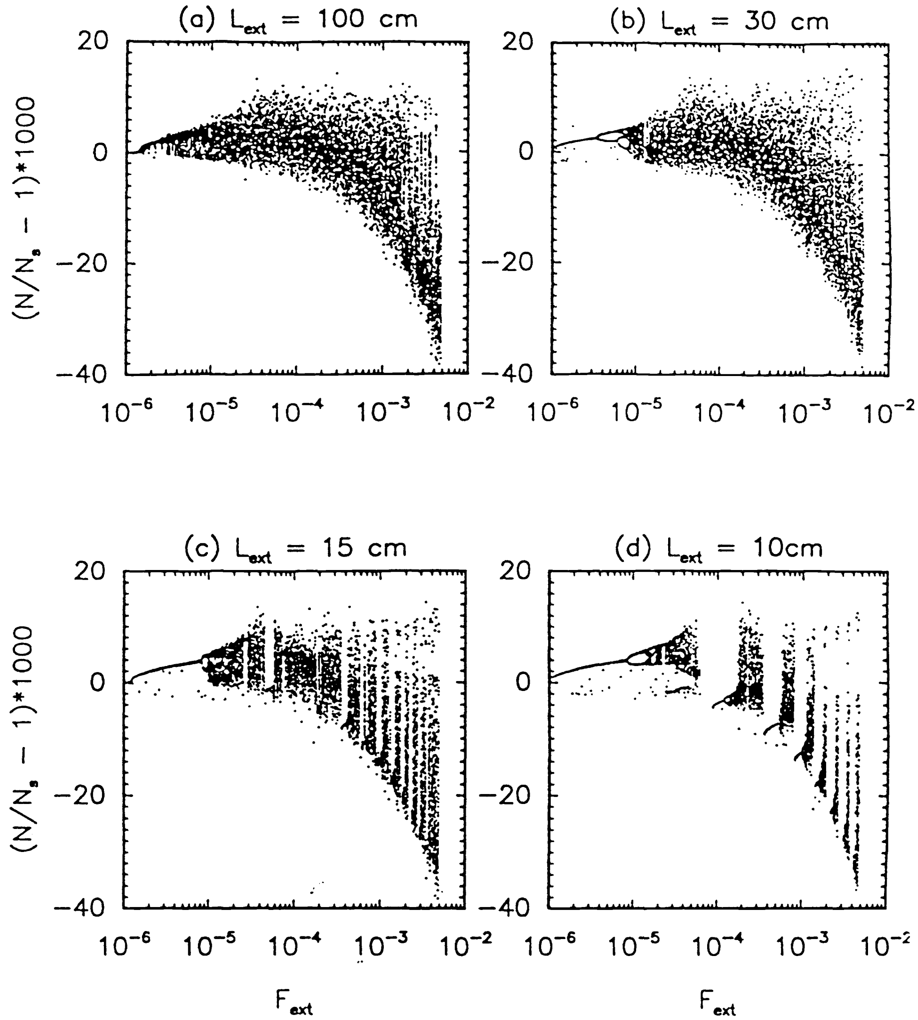


Figure 1. Bifurcation diagrams showing the carrier number N (normalized to the solitary laser value N_S) as a function of F_{ext} for a single-mode semiconductor laser for L_{ext} in the range 10-100 cm. The output power is 1.6 mW and $\alpha = 4$.

enters a second chaotic region for $F_{ext} > 1.5 \times 10^{-4}$. This scenario is repeated many times. However, the route to chaos is the quasi-periodic type for higher OFB levels. Thus, the same laser can exhibit a period-doubling or a quasi-periodic route depending on the OFB level. We note that different chaotic windows in Figs. 1(c) and 1(d) are of roughly the same size when F_{ext} is plotted on a linear scale.

3. CONTROL OF OFB-INDUCED CHAOS

The existence of the chaotic regions is particularly debilitating for SLs in applications. This is due to the fact that greatly increased intensity, frequency and phase noise accompanies the onset of chaos. It is therefore of great practical concern if the chaotic regions could be eliminated or at least delayed to very large values of OFB. In this section three different methods of achieving this goal will be described. Two of the methods are "active" in the sense that a particular laser parameter (the laser current in this case) is perturbed somewhat in order to keep the laser from making the transition to chaos. The third method may be considered passive, since it relies on changes in laser and system design parameters in order to make the laser less susceptible to OFB.

3.1 High-frequency injection

A technique for controlling chaos which has found use in the optical recording industry is termed high-frequency injection or HFI.[17,19-25] Indeed, many commercial optical recording heads utilize HFI to suppress the high RIN (Relative-Intensity Noise) values that accompany optical chaos. HFI consists of sinusoidal (or square wave) modulation of the laser current. This section describes the modeling of the noise reduction achieved with HFI and makes comparison with experimental results. In general the multimode versions of Eq. (1) and (2) are used in the modeling, where Eq. (2) is modified by replacing the drive current I by

$$I(t) = I_b + I_m \sin(2\pi f_m t), \tag{8}$$

where I_b is the bias current, I_m is the modulation current, and f_m is the frequency of modulation.

Figure 2(a) shows the variation of low-frequency RIN with the OFB level for three different modulation frequencies: 0 (no modulation), 275 and 500 MHz. The unmodulated case shows vividly one of the main problems associated with OFB; namely, the intensity noise increases rapidly as the OFB increases. The low values of RIN appearing on the no-modulation curve correspond to the frequency locked states seen in the bifurcation diagram, Fig. 1(d). We note that such stable frequency-locked regions that are sandwiched between chaotic regions for short external cavities are of little practical significance. This is due to the fact that the windows are typically not very wide and the strength of feedback is rarely constant, due to unavoidable system variations. The remaining curves in Fig. 2(a) are for 20 mA peak to peak modulation. Although RIN is reduced for f_m = 275 MHz, the choice of 500 MHz is much better since the RIN is close to the solitary-laser value over a large range of OFB. As observed also experimentally [23], the ability to suppress the RIN enhancement is sensitive to the choice of the modulation frequency.

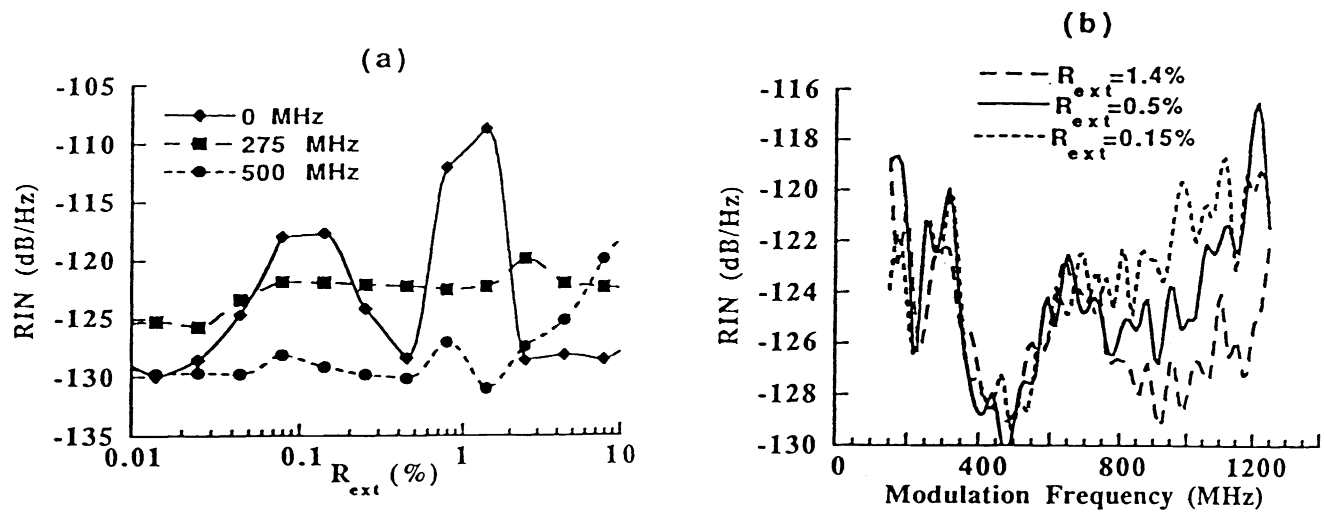


Figure 2. Dependence of low-frequency RIN on modulation frequency. (a) RIN vs. OFB for three modulation frequencies. (b) RIN vs. modulation frequency for 3 values of OFB levels.

Which modulation frequency works best for control of chaos? The answer depends critically on the external cavity length. In the long external cavity limit ($\nu_{ext} < \nu_R$) modulation at a frequency near $\nu_{ext}/2$ appears to work well, since the laser is essentially turned off at the time the OFB returns to the laser [19]. For short external cavities, however, this simple formula does not work as well. Instead, to determine the optimum modulation frequency, the low-frequency RIN is plotted in Fig. 2(b) as a function of modulation frequency for three different feedback levels chosen such that they cover both chaotic windows and the non-chaotic region between them. For this particular laser the optimum modulation frequency appears to be 480 MHz, which is far from the value of $\nu_{ext}/2$ = 750 MHz. The RIN suppression is also sensitive to modulation current. The lowest values of RIN occur for relatively large values of I_m chosen such that the laser is driven considerably below threshold, and generally the RIN suppression improves as the modulation current is increased. These results demonstrate that it is possible to eliminate the feedback-induced RIN enhancement over a broad range of feedback levels by using the HFI technique.

To compare the theoretical predictions with experiments, we have carried out measurements of the low-frequency RIN of an optical recording diode laser as a function of OFB using a range of modulation frequencies and depths. As in the simulations, the external cavity length is 10 cm. The OFB level is varied in the range of 0.1-10%, while the laser power is kept constant at 1.6 mW. In the experimental plots, each data point represents an average of the measurements of ten identical lasers. By measuring the small-signal modulation response, we have determined that only approximately 60% of the modulation current at 500 MHz is effective in driving the laser. This should be kept in mind when comparing the modulation currents employed experimentally with those of the simulations. Figure 3 shows RIN vs. OFB for several different modulation frequencies, using a modulation current of 40 mA (peak-to-peak). Of the five modulation frequencies shown, 480 MHz results in by far the greatest suppression of the RIN enhancement: the RIN remains below −125 dB/Hz up to 5% OFB. Recall that the computer simulations predict (see Fig. 2(b)) that a modulation frequency in the range 450-500 MHz gives the lowest values of RIN. Typical two-sided error bars for this plot are 3-4 dB. In general, excellent agreement between theory and experiment is obtained using for the technique of HFI.[25]

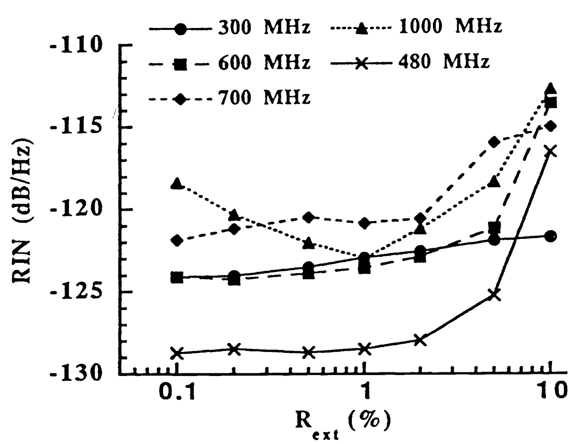


Figure 3. Experimental low-frequency RIN vs. OFB using 40 mA p-p sinusoidal modulation.

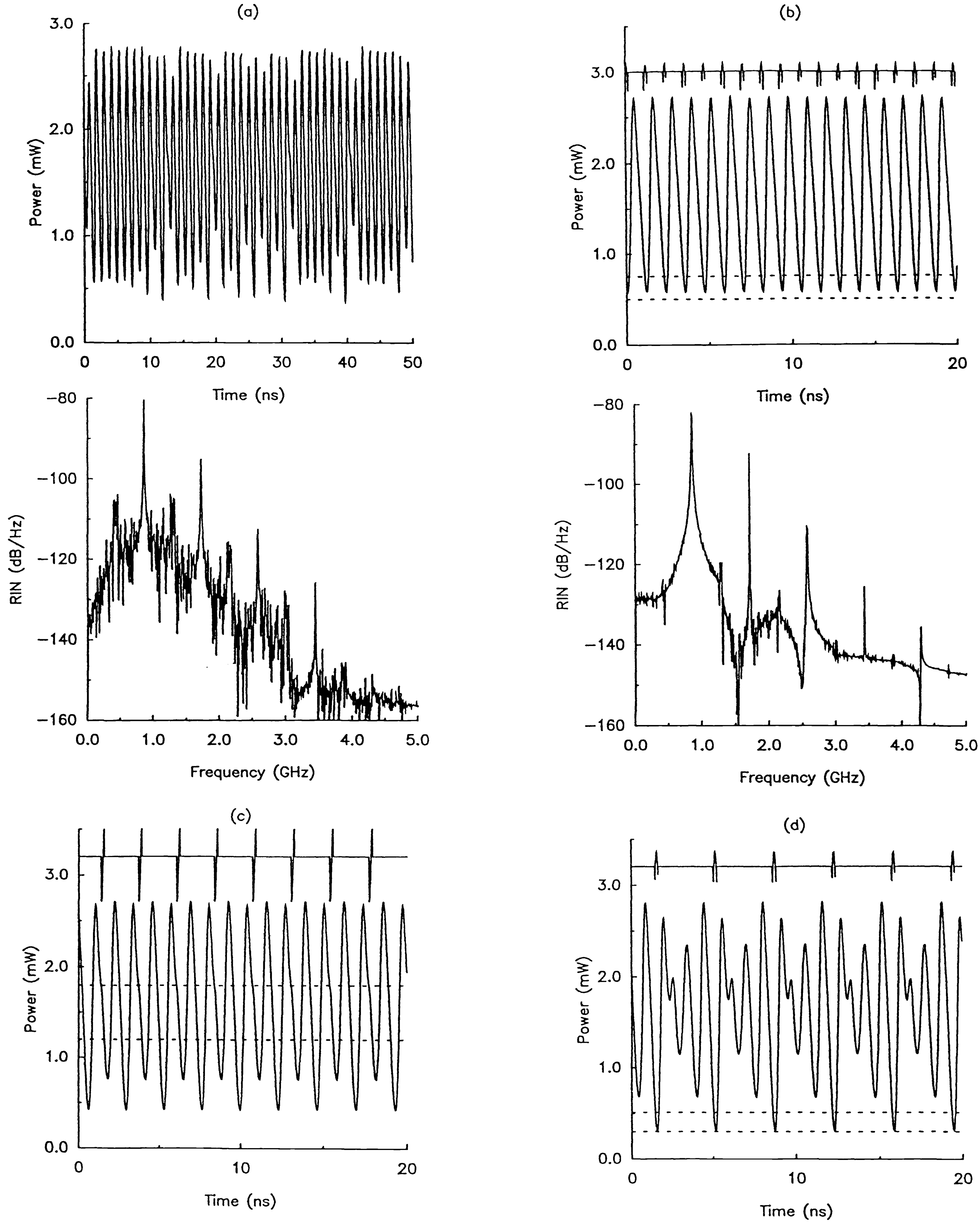
With the use of the HFI technique, the onset of optical chaos can be avoided till large values of feedback. However, this technique has undesirable properties as well. The modulation of the laser at such high frequencies and with a modulation depth large enough to turn the laser off requires a substantial amount of rf power, creates electromagnetic interference (EMI) and adds substantially to the overall system cost. Furthermore, such deep modulation greatly reduces the life of the laser diode. Note that this technique, which at least works for optical recording, is not applicable to such applications as optical or data communication, for which the basic data rate is already in the gigahertz range. Obviously, it would be desirable to find alternative techniques for controlling chaos in SLs operating with OFB. Two additional techniques are discussed in the following sections.

3.2 Occasional proportional feedback (OPF)

The presence of chaos exists, of course, in systems other than semiconductor lasers with OFB. In fact, many disciplines has shown interest in the ability to control or suppress the chaotic output of a system. One technique which has attracted considerable attention lately is termed occasional proportional feedback or OPF.[26-29] For use with a laser exhibiting chaos, OPF involves sampling the laser power periodically, and if the power falls into a given window, the laser pump is modulated with a signal proportional to the difference between the laser power and the center of the window.[27] This idea is actually a slight modification of a groundbreaking method first proposed by Ott, Gregobi and Yorke.[28,30] The OPF method has been used with tremendous success in a variety of chaotic systems. For example, in a driven diode resonator, the OPF method allowed the stabilization of orbits greater than period 20.[26] Similarly, in a laser diode pumped Nd:YAG laser, the method allowed the stabilization of a variety of periodic orbits.[27] The technique was also used in the YAG laser system to completely eradicate chaos and allow the laser to operate continuously over a wide range of output powers.[29]

One of the important elements of the OPF control method is the choice of the sampling frequency. In the systems stabilized to date with OPF, the sampling frequency has been chosen to be near the natural resonance frequency of the system. For a laser, the resonance frequency is termed the relaxation-oscillation frequency, and it accounts for the periodic exchange of energy between the atomic or molecular state (population inversion) and the electromagnetic state (light). For the above mentioned YAG laser system, this frequency is on the order of 100 kHz, making the feedback loop easy to construct electronically. Semiconductor lasers, on the other hand, possess relaxation-oscillation frequencies 4 orders of magnitude higher, on the order of 1 GHz, making the electronic application of the feedback somewhat more difficult. Nevertheless, the technique is certainly applicable in principle, and as an example of this, we apply it to our model of SLs with OFB, which was described in section 2.1.

The implementation is basically the same as described above and in reference 27. At a given frequency the laser power is sampled, and when it falls within a user-prescribed window, then a control signal is constructed. The laser current was never perturbed by more than 5% in order to stabilize the waveforms; the "modulation" is thus significantly smaller than the HFI technique discussed in the previous section. Figure 4 shows several waveforms that were able to be stabilized with the OPF method. Figure 4(a) shows the laser output when no control is applied. The undamped relaxation oscillations are apparent in the figure, but the waveform appears as a highly periodic (e.g. greater than period 4) orbit. The associated RIN spectrum shows the resonance frequency, ν_R, to be slightly above 800 MHz, but many other frequencies are present as well. Note that the vertical scale on the noise spectra is logarithmic. Figure 4(b) reveals a period one state when the control parameters have been suitably adjusted. The dotted lines in Fig. 4(b)-(d) indicate the window used for the control, and the uppermost curve is a replica of the control waveform (amplified by 10 dB and shifted for clarity). To stabilize the period 1 waveform, the sampling frequency was chosen to be 857.6 MHz, which is close to the relaxation-oscillation frequency of the solitary laser. The associated RIN spectrum reveals a much "cleaner" relaxation-oscillation frequency and harmonics, without the presence of other frequencies. Waveforms of period 2 (Fig. 4(c)) and period 4 (Fig. 4(d)) were also similarly obtained, though with different control parameters. Although the period 2 waveform was sampled at nearly $\nu_R/2$, the sampling


(a)
Power (mW)
Time (ns)
RIN (dB/Hz)
Frequency (GHz)
(b)
Power (mW)
Time (ns)
RIN (dB/Hz)
Frequency (GHz)
(c)
Power (mW)
Time (ns)
(d)
Power (mW)
Time (ns)

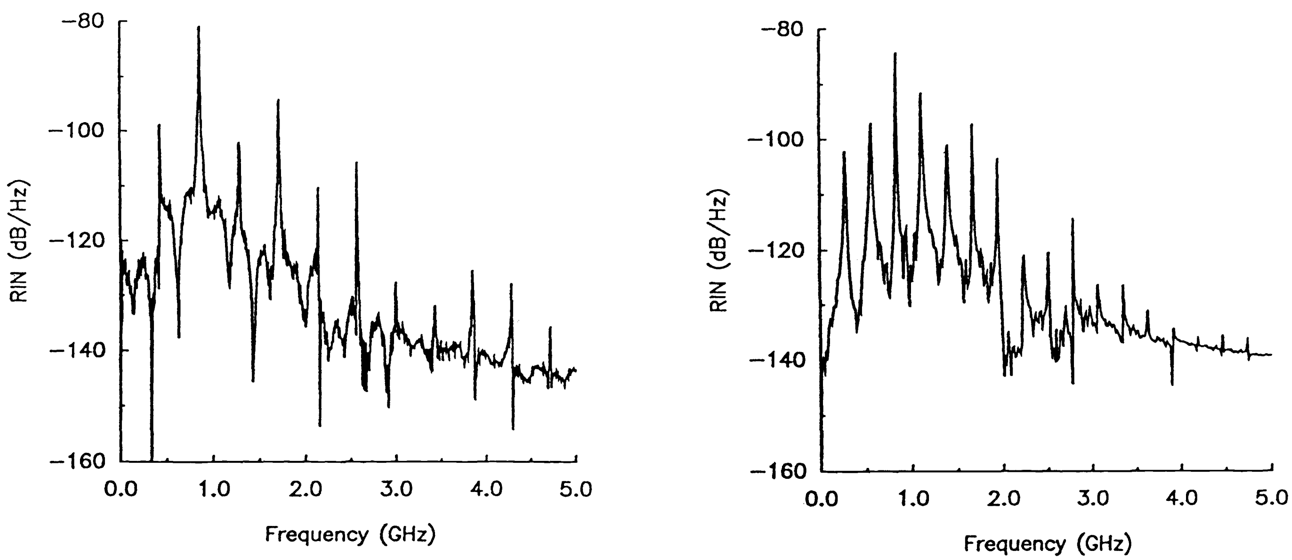


Figure 4. Power vs. time trajectories and associated RIN for (a) no control, and OPF control optimized for (b) period 1, (c) period 2, and (d) period 4 behavior.

frequency for the period 4 waveform was 847.4 MHz, close to ν_R and with a window only slightly different from that used for period 1. The period 4 waveform is only stable for about 60 ns, however; this appears to be due to the quasi-periodic nature of the laser's route to chaos, rather than the lack of optimizing the control parameters.

Although the OPF method can be applied theoretically to the case of SLs operating in the presence of OFB, there remain at least two drawbacks. First is the extremely high sampling frequency necessary to maintain control. Since SLs possess relaxation-oscillation frequencies on the order of 1 GHz, rather fast electronics will be necessary to implement this technique experimentally. The second method involves the noise that is present in semiconductor lasers. All lasers possess spontaneous-emission noise but SLs are dominated by it. In fact, the rate of spontaneous emission for semiconductor lasers is generally quite a bit higher than for other lasers. The examples of control shown in Fig. 4 were implemented with the noise sources turned off for simplicity; however, we have not been able to make the OPF method work with the noise sources turned on, even when the noise strength was made smaller than realistic values. We do not say the OPF method will not work for SLs in the presence of noise, only that it is surely more difficult to find the correct control parameters. The point should be made, however, that finding the correct values becomes quite tedious in the simulations. In contrast, in experimental implementations of OPF, the controls are typically analog, so that one may simply make small adjustments to the various controls until the correct values are found. In the simulations, on the other hand, the control parameters are input to the program, the program is run, and this is repeated with new values over and over until the desired non-chaotic output is obtained.

3.3 Laser and system optimization for eliminating chaos

In the previous two sections, we described two techniques for control of chaos in SLs with OFB which consisted of active perturbation to the laser current. In this section we address the question of whether the laser can be rendered insensitive to OFB merely by changing the design of the system or of the laser itself. This would seem to be an admirable goal, considering the problems associated with the active techniques already described. To this end, we consider which parameters are most important for the transition to chaos.

In section 2.2 we noted that the occurrence of chaos was delayed as the length of the external cavity was reduced. At the same time, the chaotic regions were interrupted more and more frequently by stable windows. In fact it can be shown that for external cavities such that $\nu_R < 0.1\nu_{ext}$, chaos is effectively avoided for all of the weak to moderate feedback range.[18] Of course the length of the external cavity is not always a system design parameter. For instance, in optical communications OFB may occur from the far end of a fiber or from a fiber imperfection, making it difficult to achieve the short external cavity limit. On the other hand, in write-once optical recording the distance from laser to disc is about 10 cm, and for the low powers used in reading from the disc, the short cavity condition ($\nu_R < \nu_{ext}$) is satisfied. Figure 1 (c) and (d) indicate that if the distance could be decreased even further, the problems associated with OFB could be reduced.

Aside from the external cavity length, there are certain laser parameters which strongly influence the effects of OFB. Two parameters in particular are the nonlinear-gain parameter ε and the linewidth-enhancement factor α. The sensitivity on ε is not surprising since the damping rate of relaxation oscillations in semiconductor lasers is mostly governed by the nonlinear gain. The route to optical chaos begins when the OFB reduces the damping rate to the extent that relaxation oscillations become undamped. Since an increase in ε makes the steady state more stable by increasing the damping rate of relaxation oscillations, one would expect chaos to occur at higher OFB levels for larger values of ε. In general, larger values of ε cause not only the route to chaos to be delayed to higher OFB levels, [31,32] but also the location and width of the chaotic windows to differ greatly.[17]

The dependence of chaotic dynamics on the linewidth-enhancement factor α is also quite dramatic. Indeed, the laser remains stable and does not exhibit chaos when α is below a critical value that depends on many other parameters (typically $\alpha_{crit} < 1$). By contrast, chaos becomes much more dominant for large values of α.[2,17,32] For a value of $\alpha = 6$, and all other parameters unchanged, the stable windows of Fig. 1(d) almost completely disappear. The dependence of the chaotic behavior on α can be understood by noting that the parameter α governs the amplitude-phase coupling in semiconductor lasers. Since light fed back into the laser cavity is delayed in the external cavity, the OFB makes the laser much more sensitive to changes in the optical phase (OFB acts as a memory device because of its delayed nature). Any phase changes are then transformed to gain changes with proportionality constant α.

Therefore, in order to make the system less sensitive to the effects of OFB, the external cavity length and linewidth-enhancement factor should be reduced and the nonlinear gain should be increased. Strained quantum-well lasers have the potential of satisfying two of three of those requirements. They are known to have both lower values of α, due to the higher value of the gain coefficient, as well as larger nonlinear gain. Figure 5 shows a simulated comparison between an optimized optical recording head which uses a strained quantum well laser and external cavity length of 5 cm, and a standard laser with 10 cm external cavity as in Fig. 1-4. Specifically, α has been changed from 4 to 1.5 whereas ε has been increased from 5×10^{-18} cm^3 to 2×10^{-17} cm^3. Clearly, the optimized system performs in a superior manner with respect to OFB characteristics. Whereas the conventional laser is very noisy most of the time, the optimized laser RIN never goes above -120 dB/Hz. The transition to chaos and large RIN values is delayed well beyond $F_{ext} = 3\times10^{-3}$, corresponding to about 15% OFB assuming a 2% coupling efficiency.

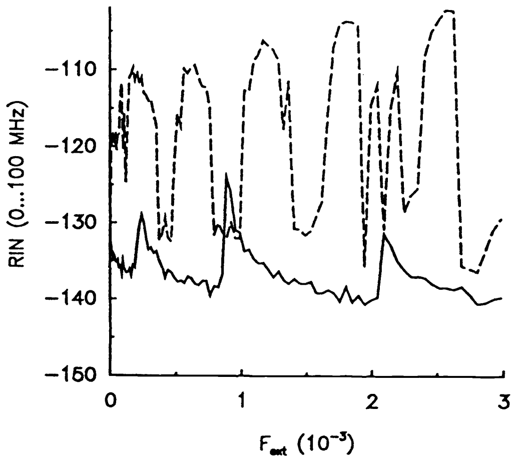


Figure 5. A comparison of low frequency RIN vs. F_{ext} between a standard laser and L_{ext} = 10 cm (dashed) and a strained, quantum-well laser and L_{ext} = 5 cm (solid). See text for details.

4. CONCLUSIONS

Semiconductor lasers (SLs) in the presence of external optical feedback exhibit a substantial increase in the low-frequency intensity noise due to a transition to optical chaos. This transition is studied as a function of external cavity length though the use of bifurcation diagrams. Generally, for short external cavities such that the $\nu_R < 1/\tau$, the chaotic regime is interrupted by multiple regions of frequency locking. The stable windows become dominant as the external cavity is made shorter.

It is extremely important for the use of semiconductor lasers in applications that the chaotic regime be avoided. We investigated three techniques which show promise in achieving this goal. The technique of high frequency injection (HFI) is well established in the optical recording industry and involves deep modulation of the laser injection current at a frequency much higher than the data rate. HFI delays the onset of chaos until high values of feedback, although the large modulation (~ 40 mA p-p at ~ 500 MHz) is hard on the laser and the system design. The technique of occasional proportional feedback (OPF), which has found use in a variety of systems including chaotic lasers, was shown through simulations to be moderately successful in stabilizing the output of SLs with OFB. Although the technique requires much smaller modulation depths than HFI, it suffers from a high modulation frequency determined from the laser's relaxation-oscillation frequency (~ 1GHz). The high rate of spontaneous emission noise present in SLs also appears to be a limiting factor in the application of OPF.

A final chaos-control technique is fundamentally different from the previous two since it requires no active modulation but only an optimization of various system and laser parameters. Specifically, to make the laser least susceptible to OFB, the external cavity length should be made short, the linewidth-enhancement factor α small and the nonlinear gain parameter ε large. The latter two requirements may be met to some degree by using strained quantum well lasers. It was shown that by optimizing these three parameters, the laser could be made relatively insensitive to the effects of OFB. Specifically, the low-frequency RIN could be maintained below -120 dB/Hz to more than 10% OFB.

5. ACKNOWLEDGMENTS

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