Route to broadband chaos in a chaotic laser diode subject to optical injection

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We experimentally and numerically demonstrate a route to bandwidth-enhanced chaos that is induced by an additional optical injection for a chaotic laser diode with optical feedback. The measured and calculated optical spectra consistently reveal that the mechanism of bandwidth enhancement is the interaction between the injection and chaotic laser field via beating. The bandwidth can be maximized only when the injected light is detuned into the edge of the optical spectrum of the chaotic laser field and the beating frequency exceeds the original bandwidth. The simulated dynamics maps indicate that 20 GHz broadband chaos can be obtained by commonly used laser diodes. © 2009 Optical Society of America

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Chaotic oscillations of laser diodes have drawn considerable attention owing to their potential applications in secure communications [1], chaotic lidar [2], optical time-domain reflectometers [3], true random number generators [4], and so on. However, the laser's relaxation oscillation limits the bandwidth of chaotic light emitted from a laser diode with single optical injection or feedback. Thus some applications, such as the transmission rate of optical chaos communications, are restricted.

This limitation has led researchers to seek ways to obtain broadband chaotic lasers. Recently, theoretical studies have predicted that an additional optical injection can enhance the bandwidth of chaotic light induced by optical or optoelectronic feedback on a laser diode [5,6]. However, the mechanism remains unclear. The former theoretical works have attributed the bandwidth increase to relaxation frequency enhancement under strong locking injection [7,8], but our previous experiments indicated that it was unlocking injection, and that the variation of injection parameters may suppress the chaotic oscillation, which may be turned into regular time-periodic dynamics or even injection locking [9]. Therefore it is desirable to have a detailed understanding about the mechanism and injection conditions, not only for the basic physics viewpoint but also for the technological applications. In this Letter, we experimentally and numerically demonstrate the route to bandwidth-enhanced chaos in a chaotic laser diode with an additional optical injection, and we disclose the underlying mechanism.

Our experimental setup has been described previously [9]. A distributed feedback (DFB) laser with a ~4 m fiber ring feedback cavity was used as a chaotic laser (the slave laser). The other solitary DFB laser was employed as an injection laser (the master laser) to enlarge the bandwidth of the chaotic laser. The slave laser was biased at 28.0 mA (1.27 times threshold), and its wavelength was stabilized at 1553.8 nm with 0.3 nm linewidth (at −20 dB) and a 35 dB side mode suppression ratio. The laser's output power was 0.7 mW, and the relaxation frequency and modulation bandwidth were about 2 GHz and 5 GHz, respectively. The original chaotic state before optical injection was obtained with −6.1 dB optical feedback. As plotted in Fig. 1(a-I), the broadened optical spectrum has 6 GHz redshift and fits frequency ranges from −18 GHz to 10 GHz. The −3 dB definition of bandwidth is not suitable since the rf spectrum in Fig. 1(a-II) is fluctuant so we adopt the bandwidth definition as the span between the dc and the frequency where 80% of the energy is contained, and the original bandwidth f_0 is 6.2 GHz. Note that we estimate the feedback injection strength with a scale of the solitary slave laser's power.

The rest of Fig. 1 displays the experimentally obtained evolution of optical and rf spectra of the chaotic laser under −4.0 dB optical injection with different frequency detuning. Shown in Figs. 1(b-I) and 1(b-II), 14 GHz detuning injection light excites high-

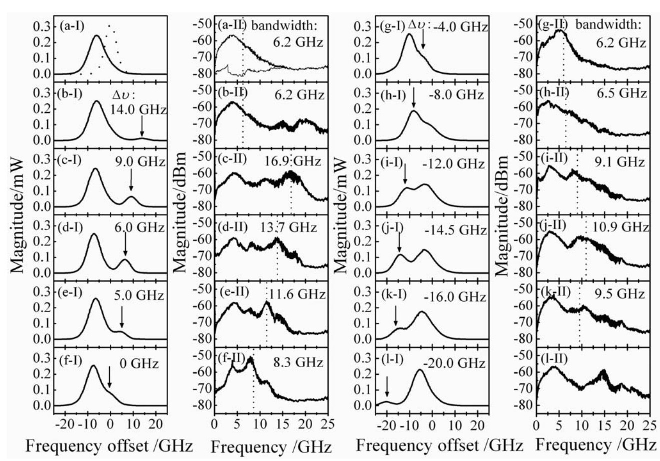

Fig. 1. Experimentally obtained evolution of the optical spectra (the first and third columns) and rf spectra (the second and fourth columns) of a chaotic laser with −6.1 dB optical feedback as −4.0 dB injection was detuned. Injecting light at the edge of the optical spectrum can enhance the bandwidth of the chaotic laser. (Resolution bandwidth is 0.06 nm and 3 MHz for optical and rf spectra.)

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frequency oscillations by beating with the chaotic laser field. But these excited oscillations being separate from chaotic oscillations in the frequency domain cannot enhance bandwidth. When detuning is reduced into the periphery of optical spectra of chaos, for instance 9.0, 6.0, 5.0, and 0 GHz, as depicted in Figs. 1(c)–1(f), the excited oscillations shift toward relaxation frequency and join with chaotic oscillations. The result is that the rf spectra are expanded and bandwidths are enhanced, for example, to 16.9 GHz in Fig. 1(c-II). Note when the frequency difference between the injection light and the laser's principal mode was below f_0, such as detuning of −4.0 GHz and −8.0 GHz in Figs. 1(g) and 1(h), bandwidths were hardly enlarged. Figures 1(i)–1(l) reveal that the further decrease of detuning leads to a similar but reversed evolution of spectra and bandwidths.

The system can be modeled by a set of rate equations for the slave laser electric complex amplitude E and carrier density N, respectively, as expressed in the following equations:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{1+i\alpha}{2}\left[\frac{g(N-N_0)}{1+\epsilon|E|^2} - \tau_p^{-1}\right]E + \frac{\kappa_f}{\tau_{\text{in}}}E(t-\tau) \times \exp(-i2\pi\nu_s\tau) + \frac{\kappa_j}{\tau_{\text{in}}}E_j\exp(i\Delta\nu t), \quad (1)$$

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{I}{qV} - \frac{N}{\tau_N} - \frac{g(N-N_0)}{1+\epsilon|E|^2}|E|^2, \quad (2)$$

where κ_f and κ_j denote the feedback and injection strength, the amplitude of injection laser $|E_j|$ is equal to that of the solitary slave laser, and $\Delta\nu = \nu_j - \nu_s$ is the detuning between the injection and the slave lasers. The feedback delay $\tau = 20$ ns is set in the corresponding experimental setup. The following parameters were used in simulations: transparency carrier density $N_0 = 0.455 \times 10^6\ \mu\text{m}^{-3}$, threshold current $I_{\text{th}} = 22$ mA, differential gain $g = 1.414 \times 10^{-3}\ \mu\text{m}^3\ \text{ns}^{-1}$, carrier lifetime $\tau_N = 2.5$ ns, photon lifetime $\tau_p = 1.17$ ps, round-trip time in laser intracavity $\tau_{in} = 7.38$ ps, linewidth enhancement factor $\alpha = 5.0$, gain saturation parameter $\varepsilon = 5 \times 10^{-5}\ \mu\text{m}^3$, and active layer volume $V = 324\ \mu\text{m}^3$. The simulated slave laser was biased at $1.7 I_{\text{th}}$ with 5.2 GHz modulation bandwidth, which is shown in the modulation response curve in Fig. 2(a-II).

As $\kappa_j = 0$, we numerically found that increasing κ_f leads to a period-doubling bifurcation route to chaos, followed by a reversed route out of chaos. The chaos region was about 0.04–0.16 of κ_f, and bandwidths were about 4.0–6.2 GHz. We selected the state of $\kappa_f = 0.12$ as the original chaos with 5.9 GHz bandwidth. Its optical spectrum with a range of −20–15 GHz in Fig. 2(a-I) is dominated by a broadened pedestal and several peaks, representing the principal mode with redshift of −6.0 GHz, undamped relaxation oscillation, and the solitary laser mode at 0 GHz. The power is mainly spread among these peaks. As a result, as shown in the rf spectrum and modulation response in

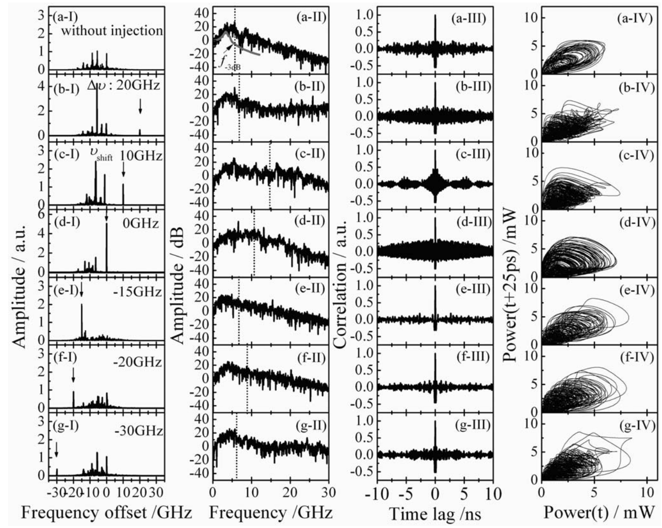

Fig. 2. Calculated optical spectra (I), rf spectra (II), autocorrelation traces (III), and phase portraits (IV) of the chaotic laser: (a) $\kappa_f = 0.12$, $\kappa_j = 0$; (b)–(g) with optical injection at different detuning and $\kappa_j = 0.15$. The route to bandwidth enhancement is in agreement with experimental results shown in Fig. 1.

Fig. 2(a-II), most oscillating energy distributes around relaxation frequency, and the bandwidth is limited to about −3 dB modulation bandwidth of the solitary laser.

We set $\kappa_j = 0.15$, which is about 2 dB more than optical feedback according to the experimental case. Figure 2 shows the simulated route to bandwidth enhancement with varying injection detuning and exhibits good agreement with experimental results in Fig. 1. As plotted in Figs. 2(c-I) and 2(c-II), the injection mode, the principal mode, and the side mode excited by relaxation oscillation interact with each other and lead to beatings corresponding to three peaks in the rf spectrum at 6.0, 12.3, and 16.2 GHz. Simultaneously, these beatings broaden their linewidth and overlap conjointly owing to the spreading optical spectrum. This phenomenon, in accordance with experimental observations, e.g., Fig. 1(c), is the very mechanism underlying the bandwidth enhancement.

In addition, the bandwidth enhancement is conditioned. Compared with the original optical spectrum, Fig. 2(e-I) shows the corresponding bandwidth increases a little bit because the injection light at −15 GHz detuning suppresses the original peaks and dominates the optical spectrum. These spectral properties are similar to experimental results of −8.0 GHz detuning plotted in Fig. 1(h). In these cases, injection light is actually injected into the center of the optical spectrum owing to the injectioninduced redshift of the laser field. Therefore we can deduce that the bandwidth can be enlarged when injection detuning is located in the edge of optical spectrum and obeys approximately the condition of $|\Delta\nu - \nu_{\text{shift}}| > f_0$, where f_0 denotes the bandwidth of original chaos, and ν_{shift} represents the injectioninduced redshift of the laser's principal mode. The minor difference between Fig. 2 and Fig. 1 is mainly because the injection strength in simulation is higher than the actual value in experiments containing the laser's output coupling efficiency.

Figure 3(a) shows the integrated effects of injection strength and detuning on the chaotic slave laser. The different colors in these dynamics maps represent bandwidths of chaotic oscillations or fundamental frequencies of other oscillations. Figure 3(a) indicates that the chaotic oscillation keeps going as light is injected in the left side of the boundary marked by black points. However, under weak injection of $\kappa_j < 0.08$, the bandwidth has no distinct increase beyond the original value of 5.9 GHz. When κ_j is increased to the boundary of the chaos region, the bandwidth will be enlarged obviously. For example, about 20 GHz broadband chaos can be obtained at detuning of around 11 GHz in the region labeled C_A. In the larger region C_B enclosed by the contour line of 8.9, the bandwidth is effectively enhanced over 1.5 times the original value. Note that, owing to the injection-induced redshift of the laser field, the bandwidth enhancement exhibits an asymmetry with respect to detuning, and positive detuning (e.g., region C_B) is more suitable for generating broadband chaos. This is also indicated by Fig. 1 and Fig. 2. The further increase of κ_j leads to transition states and subsequently, a reversed period-doubling route out of chaos and into periodic dynamics or locking. A typical transition state is displayed in Fig. 2(d-II): beating excited by injection light becomes strong and emerges clearly in the rf spectrum.

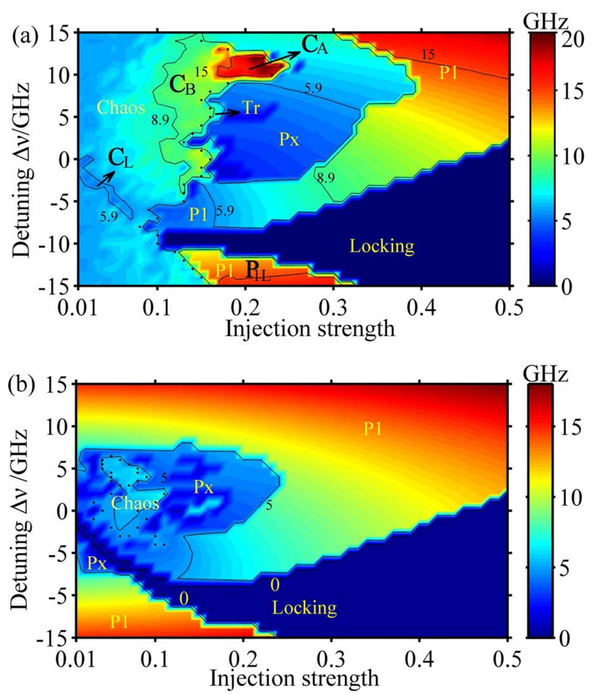

Fig. 3. (Color online) Calculated maps of bandwidth and dynamics induced by optical injection on the slave laser (a) oscillating chaotically with 5.9 GHz bandwidth at $\kappa_f = 0.12$ and (b) without optical feedback. C, chaos; P1, period one; Tr, transition states between chaos and Px; Px, unified presentation of other dynamics, e.g., period doubling and period quadrupling. The color represents bandwidths of chaotic oscillations and fundamental frequencies of other oscillations.

For comparison, the dynamics map of the slave laser without optical feedback is shown in Fig. 3(b). Obviously, the broadband chaos region C_B in Fig. 3(a) is corresponding to the part of the unlocking injection region in Fig. 3(b). Conversely, for injection in the locking region surrounded by two contour lines of 0 GHz in Fig. 3(b), the chaotic oscillation was suppressed at weak strength (region C_L), or turned into period-one oscillation (region P_{1L}) or locking at strong strength. This therefore indicates that with locking injection it may be difficult to obtain broadband chaos.

In conclusion, we experimentally and numerically study the route to broadband chaos induced by an additional optical injection on a chaotic DFB laser. Analyses of optical spectra reveal that the mechanism of bandwidth enhancement is the interaction between the injection light and the chaotic laser field by beating. Evolutions of the optical and rf spectra and dynamics maps show that unlocking injection into the periphery of the optical spectrum, especially on the plus side, is most suitable for dramatic enhancement, and the injection strength should be one to two times the feedback strength. We believe that optical injection into a chaotic laser diode is an effective, predictable, and controllable method to obtain broadband chaotic oscillations.

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