Enhancing the Bandwidth of the Optical Chaotic Signal Generated by a Semiconductor Laser With Optical Feedback

Anbang Wang, Yuncai Wang, and Hucheng He

***Abstract*—Bandwidth enhancement of chaotic signal generated from chaotic laser by using continuous-wave optical injection is experimentally demonstrated. A distributed feedback semiconductor laser with optical feedback is employed as the chaotic laser. The bandwidth of the chaotic signal is enhanced roughly three times by optical injection into the chaotic laser compared with the bandwidth when there is no optical injection.**

***Index Terms*—Bandwidth enhancement, broadband, chaos, optical feedback, optical injection, semiconductor lasers.**

I. INTRODUCTION

OPTICAL chaotic signals generated from lasers have been an attractive issue studied extensively for applications such as secure communications [1], [2], chaotic lidar/radar [3], [4], and coherence tomography [5]. One of the essential reasons is that these optical chaotic signals have broadband advantages over electrical chaotic or random signals. Semiconductor lasers, subject to optical feedback, optical injection, or optoelectronic feedback, can readily emit large-amplitude optical chaotic signals, and hence become the most suitable chaotic signal sources for the above applications. Unfortunately, the bandwidths of these optical chaotic signals generated by semiconductor lasers utilizing the above three techniques have been limited to a few gigahertz, mainly due to the low relaxation oscillation frequency of semiconductor laser. Therefore, the advantage in bandwidth of optical chaotic signal is not fully exploited. For instance, the narrow bandwidth of the optical chaotic signal limits the range resolution of chaotic lidar and the transmission rates of chaos communications.

Early studies have already demonstrated that the modulation bandwidth of laser diodes can be significantly enhanced by external strong light-locking injection [6], [7]. In recent years, theoretical studies have predicated that the bandwidth of chaotic waveform emitted from chaotic lasers can be enlarged by strong optical-locking injection [8], [9] or optoelectronic feedback [10]. It has been reported that broadband chaotic signal can be obtained by injecting chaotic light into a laser diode [11]. In this letter, we experimentally demonstrate the bandwidth enhancement of the optical chaotic signals generated by a distributed feedback (DFB) laser diode with optical feedback using external continuous-wave optical injection.

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II. EXPERIMENTS

A. Experimental Setup

Our experimental setup is shown in Fig. 1. A DFB laser diode, the slave laser, subject to optical feedback with a fiber ring cavity, is referred to as the chaotic laser. The power of feedback light can be adjusted with a variable attenuator. The polarization state of the feedback light is matched to that of the slave laser by a polarization controller PC_2. Another DFB laser diode, the injection laser, is used to enhance the bandwidth of the chaotic signal by injecting continuous-wave light into the slave laser through a 30/70 optical fiber coupler. The power and polarization state of the injection light are controlled by an erbium-doped optical fiber amplifier (EDFA) and PC_3, respectively. An optical isolator is used to prevent unwanted optical feedback into the injection laser. Both laser diodes are driven by low-noise current sources (Newport 501) and are temperature stabilized by precise temperature controllers (ILX Lightwave LDT-5412). The injection laser is wavelength adjusted with temperature controller to achieve its optical frequency detuning to the free-running slave laser, i.e., $\Delta v = v_{\rm inj} - v_{\rm s}$. A 500-MHz bandwidth oscilloscope is used to identify and monitor the chaotic oscillations in the slave laser. A spectrum analyzer (Agilent E4407B) with a 47-GHz bandwidth photodetector (u2t XPDV2020) and an optical spectrum analyzer (Agilent 86140B) are used to measure the power spectrum and optical spectrum of the emission of light from the chaotic laser, respectively. In experiments, the slave laser was biased at 1.27 times its threshold current (22 mA) and its center wavelength was stabilized at 1553.84 nm. On this condition, the free-running slave laser has about 2-GHz relaxation oscillation frequency and its output power is -1.6 dBm. The length of the fiber ring cavity was about 4 m. For the fluctuant power spectrum of chaotic waveform, the conventional -3-dB bandwidth definition is not very suitable. Here, we adopt the bandwidth definition of chaotic waveform as the span between the dc and the frequency where 80% of the energy is contained within it [10].

B. Experimental Results of Bandwidth Enhancement

The bandwidth enhancement is shown with power spectra of optical chaotic signals in Fig. 2. The spectrum of the original

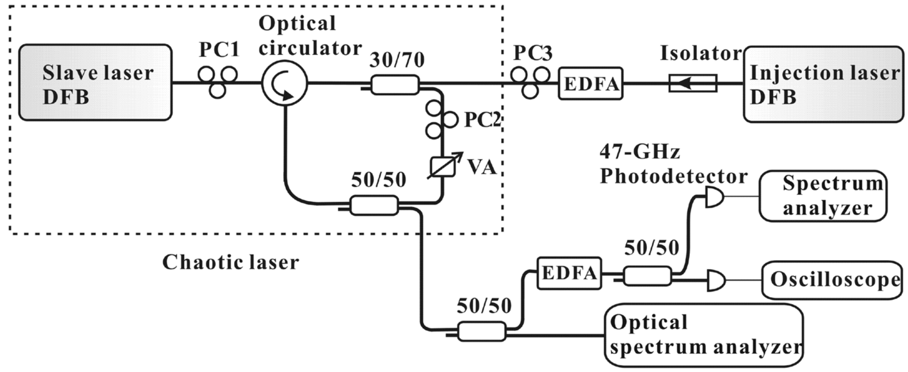

Fig. 1. Experimental setup of bandwidth enhancement of optical chaotic signal generated by chaotic laser with optical feedback using optical injection.

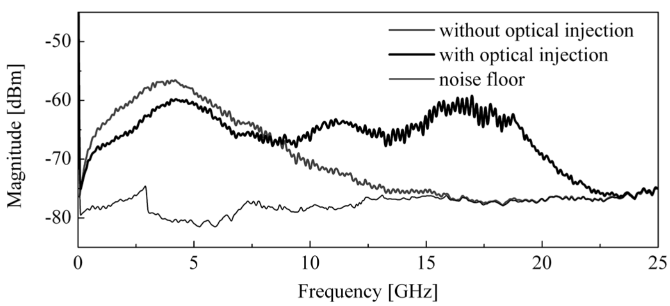

Fig. 2. Experimentally obtained spectrum of the bandwidth-enhanced chaotic signal (black bold line) with −5.6-dBm optical injection at 8.8-GHz detuning. The gray thin line denotes the spectrum of original state of the chaotic laser without optical injection. The bandwidth is enhanced from 6.2 to 16.8 GHz. (Resolution bandwidth = 3 MHz).

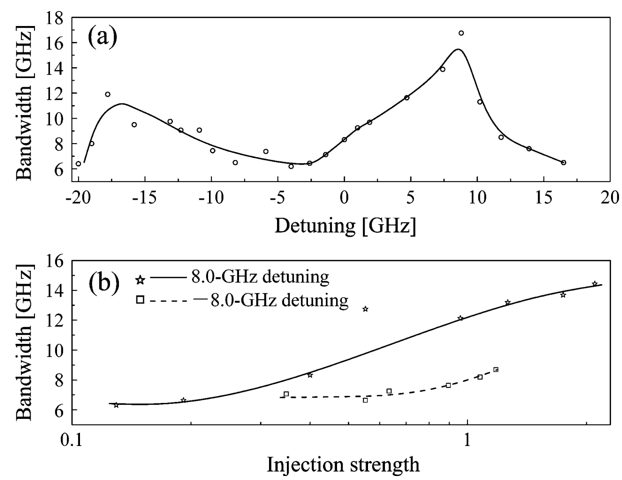

Fig. 3. (a) Experimentally enhanced bandwidths as a function of the detuning of −5.6-dBm injection light plotted with circles and fitted curve. (b) Bandwidths as a function of the injection strength at 8.0-GHz and −8.0-GHz detuning depicted with stars and squares, respectively. The solid line and the dashed line are their respective regression curves.

state of the chaotic laser without optical injection is plotted with gray thin line in Fig. 2, and this chaotic state was obtained with −7.7-dBm feedback light. Obviously, the dominative components of the spectrum are near and hence the energy mainly concentrates around the relaxation oscillation frequency. The spectrum declines rapidly over its 6.2-GHz calculated bandwidth and to the noise floor (black thin line) at about 15 GHz. Indicated by the quasi-period route to chaos of laser with optical feedback [12], and observed in our experiments, the bandwidth cannot increase largely only via increasing feedback strength. The black bold line denotes the spectrum of the bandwidth-enhanced optical chaotic signal with −5.6-dBm optical injection from the injection laser at 8.8-GHz detuning. The bandwidth is 16.8 GHz, i.e., roughly three times that of the original chaotic signal. Interestingly, the spectrum is flat: the fluctuations of its component level are limited in ±5-dBm range around −63 dBm from 1 to 20 GHz.

C. Effects of Detuning and Injection Strength on Bandwidth

The experimentally obtained bandwidths with −5.6-dBm optical injection as a function of the detuning are shown in Fig. 3(a) with circles and corresponding fitted curve. The bandwidth variation exhibits a shape of asymmetric saddle due to different physical mechanisms of bandwidth enhancement. In the detuning range of about −10 ∼ 0 GHz, the injecting light will lock the slave laser when there is no optical feedback. The laser's relaxation oscillation frequency increases due to the transient interference between injection-locked field and the red-shift cavity resonant field [6]. Therefore, this bandwidth enhancement is because of the increased relaxation frequency by optical-locking injection, as theoretically predicted by [8]. Notice that the slight increments in this detuning range are due to the weak injection power practically into laser cavity.

In contrast, in detuning ranges of about −18 ∼ −10 and 0∼12 GHz, injecting light leads to instable locking for the solitary slave laser and excites hereby undamping periodic oscillation [13] due to interference between the instable-locked field and the unsuppressed laser field. As switching on optical feedback, the periodic oscillation broadens its linewidth due to the optical spectrum-broadened chaotic laser field. Therefore, it can be indicated that the intercoupling between the high-frequency broad-linewidth periodic oscillation and the chaotic oscillation enhances the bandwidth of chaotic laser. Note that the phase-amplitude coupling determined by the linewidth enhancement factor leads to red shift of laser field in the case of optical injection. The red shift of laser's frequency results in the asymmetry of periodic oscillation frequency with respect to detuning. Consequently, the bandwidth enhancement exhibits asymmetry, and the positive detuning induces the larger enhancement effect than the negative detuning, shown in Fig. 3(a). In addition, the bandwidth cannot be increased when the detuning is too large. The reason is that the periodic oscillation has the frequency exceeding the maximum frequency of the chaotic oscillation and resultantly has little effect on its bandwidth.

Fig. 3(b) shows the bandwidths as a function of injection strength at the detuning of 8.0 GHz and −8.0 GHz with stars and squares, respectively. The solid line and the dashed line are their respective regression curves. For comparing with feedback strength, the injection strength is defined as the ratio of the power of the injection light to that of the feedback light into the slave laser. Notice that the 8.0-GHz and −8.0-GHz detuning represent the bandwidth enhancements by instable and stable locking injection, respectively.

As shown in Fig. 3(b), the bandwidths increase with increasing the injection strength in the both two cases. However, both the enhancement effect and the range of injection strength (within it the bandwidth can be enlarged) with 8.0-GHz detuning exceed greatly that with −8.0-GHz detuning. We experimentally found that 8.0-GHz detuning injection light can increase the bandwidth at injection strength from 0.12 to 2.08. As injection strength approaches 2.08, the periodic oscillations become so strong, resulting in uneven spectrum of chaotic signal. For a further increase of the injection strength, the periodic oscillations dominate the slave laser's outputs, which are not treated as chaos. In contrast, at −8.0-GHz detuning, the bandwidth can be enlarged only in the strength range of about 0.32∼1.16. As injection strength increases over 1.16, the slave laser undergoes paroxysmal chaos, quasi-periodic oscillations, and eventually is locked. Therefore, it can be indicated that the injection strength cannot exceed the feedback strength greatly for enhancing bandwidth by stable locking injection.

III. Conclusion

We have experimentally enhanced the bandwidth of optical chaotic signals emitted from a laser diode with optical feedback by injecting continuous-wave light. The bandwidth is enhanced roughly three times that of the chaotic laser without optical injection. High-frequency periodic oscillations and relaxation frequency enhancement are the physical mechanisms of bandwidth enhancement of chaotic laser by instable and stable locking injection, respectively. Experimental results also indicate that the positive detuning injection leading to high-frequency periodic oscillations are more suitable for obtaining bandwidth-enhanced chaotic signals. The injection of laser into a chaotic laser is believed to pave the way for the generation of broadband chaotic signals and promoting its technological applications.

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