Generation of Broadband Chaotic Laser Using Dual-Wavelength Optically Injected Fabry–Pérot Laser Diode With Optical Feedback

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***Abstract*—Chaotic laser with a flat power spectrum up to 32.3 GHz has been generated by using a dual-wavelength optically injected Fabry–Pérot laser diode with optical feedback. The Fabry–Pérot laser diode with fiber ring cavity is utilized to generate the chaotic light. The bandwidth of the chaotic laser, due to dual-wavelength optical injection, is enhanced roughly four times as much as that of the chaotic laser without optical injection.**

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

I. INTRODUCTION

CHAOTIC laser generated by the laser diodes has aroused considerable interest owing to its wide applications in optical chaos communications [1], chaotic lidar [2], optical time domain reflectometer (OTDR) [3], fast random bit generator [4], [5], and photonic ultra-wideband signal generator [6]. However, the relaxation oscillation limits the bandwidth of the chaotic laser emitted from a laser diode with single optical injection or feedback. Thus some applications are much restricted in the range resolution of chaotic lidar, the bit rate of random sequence, and the transmission rate of optical chaos communications.

Therefore, in past few years, some schemes for bandwidth enhancement of chaotic laser have been reported. For example, Lin *et al.* numerically studied the bandwidth enhancement of chaotic states in a semiconductor laser subject to optoelectronic feedback by using external optical injection [7]. Hosiny *et al.* represented chaos enhancement by injecting additional optical signals into an optically injected semiconductor laser [8]. Moreover, Yan reported a method to enhance chaotic carrier bandwidth of a delayed feedback semiconductor laser with an additive feedback light [9]. Uchida *et al.* demonstrated the bandwidth-enhanced chaos generation by injecting the chaotic light into a slave laser diode [10]. Takiguchi *et al.* numerically demonstrated that the bandwidth of the chaotic carrier in a semiconductor laser with optical feedback was expanded to be about three times by strong optical injection [11]. By using an additional single-beam optical injection, we achieved the bandwidth enhancement of chaotic signals generated from a distributed feedback laser diode with optical feedback [12] and also demonstrated a route to bandwidth-enhanced chaos [13]. Until now, to our best knowledge, no experimental results of bandwidth-enhanced chaotic laser over 25 GHz has been reported by using these schemes cited above.

In this letter, we propose a method to generate broadband optical chaotic signals by using dual-wavelength optical injection Fabry–Pérot laser diode with optical feedback and experimentally demonstrate the generation of chaotic laser with bandwidth up to 32.3 GHz by this scheme.

II. EXPERIMENTS

A. Experimental Setup

Fig. 1 shows the experimental setup. A Fabry–Pérot laser diode (FP-LD) subject to optical feedback with a fiber ring cavity is used to generate the chaotic light. The power of feedback light is adjusted by a variable attenuator (VA3) and an erbium-doped fiber amplifier (EDFA), and its polarization state is controlled by a polarization controller (PC3). Two distributed feedback laser diodes (DFB-LD1 and DFB-LD2) are employed to enhance the bandwidth of the chaotic light by injecting continuous-wave light into the FP-LD through two 50/50 couplers. The wavelength of each DFB-LD is adjusted by a temperature controller to achieve the optical frequency detuning to the FP-LD. The power and polarization state of the injection lights are controlled by VA1, PC1, VA2 and PC2, respectively. The output of the chaotic laser is converted into chaotic radio signals by a 50-GHz bandwidth photodetector (u^2t XPDV2020). A 6 GHz bandwidth oscilloscope (LeCroy

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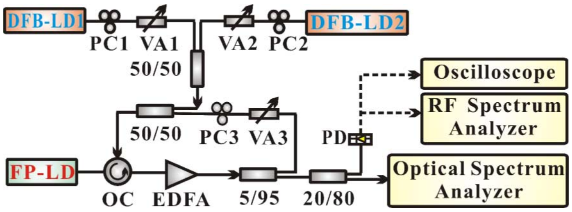

Fig. 1. Experimental setup for broadband chaotic laser generation. OC: optical circulator.

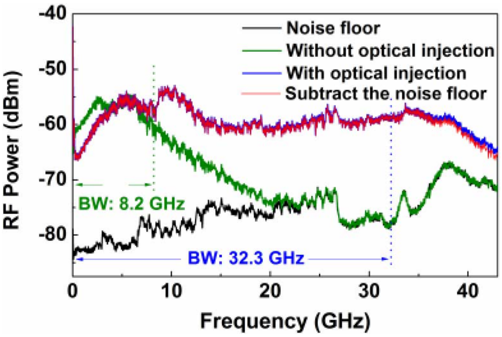

Fig. 2. Experimentally obtained spectrum of the broadband chaotic laser signal with -2.11-dBm injection power at 25.4- and 32.9-GHz detuning. The bandwidth is enhanced from 8.2 to 32.3 GHz. (Resolution bandwidth: 1 MHz; video bandwidth: 1 kHz.)

8600A), a 42.98 GHz bandwidth spectrum analyzer (Agilent E4447A) and an optical spectrum analyzer (AQ6370B) are used to measure the waveforms, rf spectrum and optical spectrum of the chaotic signal. In experiments, the FP-LD biased at 1.27 times its threshold current.

B. Broadband Chaotic Laser Generation

Fig. 2 shows the bandwidth enhancement of the power spectra of optical chaotic signals. The green line denotes the spectrum of the original chaotic laser without optical injection. The energy of the spectrum mainly concentrates around the relaxation oscillation frequency. We define the bandwidth of chaotic signals as the span between the DC and the frequency where 80% of the energy is contained [7]. The bandwidth of the original chaotic laser is 8.2 GHz, and its spectrum rapidly declines to the noise floor (black line) at about 20 GHz. The blue line denotes the measured power spectrum of the bandwidth-enhanced optical chaotic signal with the bandwidth of 32.3 GHz, i.e., about four times as much as that of the original chaotic signals. Here, the total injection power of DFB LDs is equal to -2.11 dBm and their frequency detuning to the FP-LD is 25.4 GHz and 32.9 GHz, respectively. Note that the power spectrum is almost flat: the fluctuations of its component level are limited in ± 3.5 dB range around -57 dBm from 2 to 38 GHz. In order to eliminate the effect of the spectrum analyzer noise, we subtract the noise floor from the measured power spectrum of broadband chaotic laser. And the results are denoted by the red line in Fig. 2 which almost covered the blue line from 0 to 36 GHz. Compared with previous results in [12], the power spectrum of chaotic laser becomes flatter and its bandwidth is broader, which are attributed to the dual-wavelength injection.

This result of bandwidth enhancement can be understood by considering the optical spectrum variety of chaotic laser.

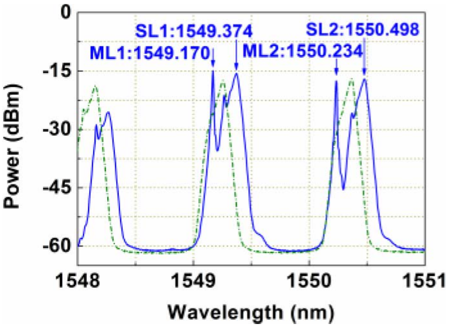

Fig. 3. Measured optical spectrum of the chaotic laser. Blue line: with dual-wavelength injection. Green line: without optical injection.

Compared with the free running state, due to optical feedback, each longitude mode of FP-LD undergoes red-shift resulted from the change of carrier density, and many extended cavity modes (ECMs) are excited. Then the FP-LD evolves into chaotic oscillations with broadened optical frequency components as the green dash-dot line presented in Fig. 3, corresponding to the original chaotic laser in Fig. 2. When two wavelengths lights inject into this chaotic FP-LD, the longitudinal modes will also undergo red-shift induced by the change of carrier density, as the blue line shown in Fig. 3, which correspond to the bandwidth-enhanced chaotic signals in Fig. 2. The DFB-LD1 (ML1: 1549.170 nm) has a 0.204 nm wavelength detuning to the FP-LD (SL1: 1549.374 nm), corresponding to 25.4 GHz frequency detuning. The DFB-LD2 (ML2: 1550.234 nm) has a 0.264 nm wavelength detuning to the FP-LD (SL2: 1550.498 nm), corresponding to 32.9 GHz frequency detuning. Obviously, the FP-LD works at unlocked state because its output optical spectrum still contains multilongitudinal modes. The beating interaction between the two injected lights, their neighboring longitudinal modes and the ECMs causes the high-frequency oscillations with broad linewidth around about 27 GHz and 34 GHz. And then the intercoupling between the high-frequency oscillations and the original chaotic oscillation makes the bandwidth of the chaotic laser enhanced greatly.

The broadband chaotic laser has a quite low power spectrum in the low frequency part $(< 2$ GHz$)$. For chaotic lidar [2] and chaotic OTDR [3], this will decrease the sidelobe levels of the correlation traces. But then the antiphase dynamics contained on individual modes may increase the lower frequency power as in [14] as opposed to using a specially designed laser. However, this does not affect its application in random bit generation [4], [10], and even is useful for generating ultra-wideband signal [6]. Moreover, the optical spectrum of the proposed chaotic laser has multiple cavity modes. For some applications, for example, the optical chaos communications, the broad optical spectrum will deteriorate the system performance due to its large dispersion in the fiber. So, the dispersion compensation technique should be introduced to solve this problem.

C. Effects of Injection Strength and Detuning on Bandwidth

Fig. 4(a) shows the bandwidths as a function of the detuning. The green trace presents the detuning between the DFB-LD1 and the FP-LD when the injection power is -3.42 dBm and the

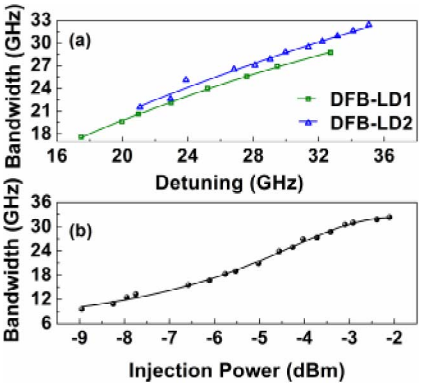

Fig. 4. (a) Effects of frequency detuning on the chaotic laser bandwidth. The green trace presents the detuning between the DFB-LD1 and the FP-LD, while the injection power is -3.42 dBm, and the detuning of DFB-LD2 is fixed at 17.5 GHz; the blue trace describes the detuning between the DFB-LD2 and the FP-LD, while the injection power is -2.92 dBm, and the detuning of DFB-LD1 is fixed at 20.9 GHz. (b) The dependence of bandwidth on the injection power. The two light injection detuning are 25.4 and 32.9 GHz.

detuning of DFB-LD2 is fixed at 17.5 GHz. As the detuning increases from 17.4 to 32.7 GHz, the bandwidth increases from 17.6 to 28.7 GHz. The blue trace describes the detuning between the DFB-LD2 and the FP-LD when the injection power is -2.92 dBm and the detuning of DFB-LD1 is fixed at 20.9 GHz. As the detuning increases from 21.1 to 35.1 GHz, the bandwidth increases from 21.5 to 32.3 GHz. We can see that in the certain frequency range of detuning, the bandwidth exhibits a linear relationship with the frequency detuning. This is because the frequency of bandwidth-enhanced chaotic laser is mainly determined by the beat effect. As the detuning increase, the frequency of the oscillation excited by the beat effect will increase linearly. In the certain frequency detuning range, the beating oscillation dominates the bandwidth of the chaotic laser, and then the bandwidth almost exhibits a linear relationship with the frequency detuning. However, when the detuning becomes larger beyond the frequency range, the bandwidth will stop increasing. This is because the excited high-frequency oscillations decouple from the original chaotic oscillations in the frequency domain and have little effect on its bandwidth. The above results qualitatively conform to our previous results [12], [13].

Fig. 4(b) shows the bandwidths as a function of injection strength. The DFB-LD1 and DFB-LD2 work at the wavelengths of 1549.170 and 1550.234 nm respectively, which correspond to the frequency detuning to FP-LD of 25.4 GHz and 32.9 GHz. Under this condition, we found experimentally that the bandwidth of chaotic laser could be enhanced from 8.2 GHz to 32.3 GHz with the injection power variation from -8.96 dBm to -2.11 dBm. For a further increase of injection strength, the oscillating state of FP-LD will transit from chaotic oscillation to quasi-periodic oscillation, or even injection locking.

Although we had constructed a mapping of the dynamics and bandwidth for a single-beam injected laser diode with optical feedback [13], the dynamics of an optically injected laser diode with more than one injection beam are much more complicated than those of a single-beam injected laser diode [15]. Furthermore, there has been no report on the dynamics of our proposed dual-wavelength optically injected laser diode with optical feedback so far. The detailed analytical explanation of the chaotic laser bandwidth enhancement by this scheme will be addressed in future publications.

III. CONCLUSION

We propose a scheme for enhancing the bandwidth of optical chaotic signals generated from a Fabry–Pérot laser diode with optical feedback by using dual-wavelength optical injection, and demonstrate experimentally the generation of broadband chaotic laser up to 32.3 GHz by this method. The bandwidth is enhanced roughly four times as much as that of the chaotic laser without optical injection due to the intercoupling between the original chaotic oscillation and the high-frequency oscillations induced by dual-beam optical injection. The broadband chaotic laser has potential for improving the range resolution of chaotic lidar, the bit rate of random sequence and the transmission rate of optical chaos communications.

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