Invited Paper

Wideband and flat-spectrum chaos generation from a semiconductor laser with strong dispersive light feedback

Longsheng Wang^{1,2}, Qingqing He^{1,2}, Anbang Wang^{1,2}, and Yuncai Wang^{1,3,4 a)}

¹ Key Laboratory of Advanced Transducers and Intelligent Control System, Ministry of Education and Shanxi Province, Taiyuan 030024, China

² College of Physics and Optoelectronics, Taiyuan University of Technology, Taiyuan 030024, China

³ School of Information Engineering, Guangdong University of Technology, Guangzhou 510006, China

⁴ Guangdong Provincial Key Laboratory of Photonics Information Technology, Guangzhou 510006, China

^{a)} wangyc@gdut.edu.cn

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Abstract: We propose and experimentally demonstrate a method of generating wideband and flat-spectrum chaos from a simple device configuration composed of a semiconductor laser subject to strong dispersive light feedback from a chirped fiber Bragg grating (CFBG). The dispersive feedback light induces external-cavity modes with irregular mode separations which beat with the internal modes of laser. This physical process of beating introduces more high-frequency oscillations and thus removes the domination of relaxation oscillation, widening and flattening the radio-frequency spectrum. Experimental results show that laser chaos with a 3-dB bandwidth of 24 GHz can be obtained at a feedback strength of 1.60, which is three times the bandwidth at a feedback strength of 0.35. Effects of the dispersive feedback strength and the wavelength detuning between the laser and the CFBG on the 3-dB bandwidth are studied.

Key Words: semiconductor laser, dispersive light feedback, laser chaos, bandwidth enhancement

1. Introduction

Laser chaos has attracted widespread attention because of its excellent signal characteristics [1–3] and important applications in the field of information security. For example, by using laser chaos as message carrier, a field experiment of high-speed secure communication at a rate of 1 Gb/s was demonstrated over 120-km fiber link in the metropolitan area network of Athens [4]. Fast random

number generation at a rate of 1.7 Gb/s was demonstrated experimentally by using laser chaos as entropy source [5], and 182-kb/s key distribution was achieved by further combining with chaos synchronization [6]. For these applications, one usually utilizes a semiconductor laser with external mirror feedback to generate the laser chaos in view of its simple and integratable device configuration. Unfortunately, it has been proven that the chaotic output from such a device configuration is usually dominated by the laser relaxation oscillation, yielding a sharp radio-frequency (RF) spectrum and limiting the chaos bandwidth to several gigahertz [7, 8]. This limitation thus becomes a main obstacle in improving the rates of secure communication, random number generation, and key distribution [9–14]. Moreover, the sharp RF spectrum means an undesirable flatness which decreases the unpredictability of laser chaos [15, 16] and thus induces security flaw to the aforementioned applications.

In recent years, much effort has been devoted to expanding the RF spectrum of laser chaos. For instance, the methods of optical injection including chaos injection [17–19], continuous-wave injection [20], dual-wavelength injection [21], mutual injection [22], and the methods of optical feedback like phase-conjugate feedback [23], filtered feedback [24] have been proposed to enhance the chaos bandwidth beyond 10 GHz. These methods are proved to be efficient in improving the bandwidth of chaotic RF spectrum. But, from the point view of spectrum flatness, they are not so satisfying because many harmonic peaks appear in the spectrum profile, yielding a flatness significantly higher than 3 dB. Therefore, the methods of delayed self-interference [25], fiber ring resonator [26, 27], optical heterodyning [28], optical time lens [29], fiber propagation [30], optical filter [31], self-phase-modulated feedback [32], highly nonlinear fiber [33] are successively proposed to simultaneously widen and flatten the RF spectrum, yielding a spectrum bandwidth approximately at 10 GHz or beyond while maintaining a spectrum flatness around 3 dB. Nevertheless, these methods usually have complex device configurations and require delicate operations because multi parameters should be matched. It is therefore interesting to find a method to generate wideband and flat-spectrum chaos with a simple device configuration and easy operations.

Our previous work found that a simple device configuration composed of a semiconductor laser subject to dispersive light feedback from a chirped fiber Bragg grating (CFBG) can readily generate laser chaos without time-delay signature [34]. Here, we further demonstrated experimentally that this configuration can widen and flatten the RF spectrum, achieving laser chaos with a 3-dB bandwidth of 24 GHz. We attribute it to the physical process of beating between the irregular external-cavity modes induced by the dispersive feedback light and the internal modes of laser under a strong feedback strength. Effects of the dispersive feedback strength and the wavelength detuning between the laser and the CFBG on the 3-dB bandwidth are investigated.

2. Experimental setup

Figure 1 shows the experimental setup of generating the wideband and flat-spectrum chaos. The emission of a distributed feedback (DFB) semiconductor laser, after being amplified by an erbium-doped fiber amplifier (EDFA), is divided by an optical coupler (OC) into two paths: one (50%) is used as output, and the other as feedback light. In the feedback path, a CFBG is arranged to make the feedback light frequency-dependent and return it into the laser cavity to induce chaos. The strength and the polarization of the feedback light are adjusted by a variable optical attenuator (VOA) and a polarization controller (PC), respectively. In experiment, the DFB laser (Eblana, EP-1550-DM) has a threshold of 13.3 mA and is biased at 26.9 mA by a laser driver (ILX Lightwave, LDX-3412), emitting with an optical power of 2 mW. The central wavelength of the free-running DFB laser is stabilized at 1549.64 nm by a temperature controller (ILX Lightwave LDT-5412). The CFBG is customized with a linewidth of 0.36 nm and a dispersion of about -1541 ps/nm which is measured with phase shift method [35], and its central wavelength is 1549.76 nm. The feedback loop comprised by the CFBG and the DFB laser has a round-trip time of 120 ns. The optical spectra of chaotic outputs are observed by an optical spectrum analyzer with a resolution of 1.12 pm (OSA, APEX, AP2041-B). Their RF spectra and temporal waveforms, after being converted into electrical signals by 50-GHz photodetectors (PD, Finisar, XPDV2120R), are measured by a 50-GHz electrical spectrum analyzer

Fig. 1. Experimental setup. DFB: distributed feedback semiconductor laser, PC: polarization controller, CIR: circulator, EDFA: erbium-doped fiber amplifier, OC: optical coupler, CFBG: chirped fiber Bragg grating, VOA: variable optical attenuator, PD: photodetector, OSA: optical spectrum analyzer, ESA: electrical spectrum analyzer, OSC: oscilloscope.

(ESA, Rohde and Schwarz, FSW) and a 36-GHz real-time oscilloscope with a sampling rate of 80 GS/s (OSC, LeCroy, LABMASTER10ZI), respectively.

3. Experimental results

We first present the temporal waveforms and auto-correlation functions (ACFs) of laser chaos with a weak dispersive feedback strength of 0.35 (first row) and a strong dispersive feedback strength of 1.60 (second row). Here, the feedback strength is equal to the power ratio of the feedback light to the laser output, and the scenario with feedback strength not lower than the critical value of yielding the largest bandwidth enhancement is defined as the strong feedback, and the scenario with feedback strength lower than the critical value is defined as the weak feedback. By comparing the temporal waveforms in Figs. 2(a) and 2(c), it is found that the latter has a much faster irregular oscillation than the former. This is due to the effect of bandwidth enhancement in the scenario of strong dispersive feedback, which introduces more high-frequency oscillations and will be illustrated later. Furthermore, as shown in Fig. 2(b), the ACF trace shows an obvious oscillation peak after the main peak at zero lag in the scenario of weak dispersive feedback, whose location equals the reciprocal of laser relaxation oscillation frequency (f_{RO}). It implies that the laser relaxation oscillation dominates the laser chaos. By contrast, as shown by the results of strong dispersive feedback in Fig. 2(d), the ACF trace no longer has relaxation oscillation peak like that of Fig. 2(b), which proves that the domination of laser relaxation oscillation is removed.

We further examine the spectral characteristics of laser chaos in the scenarios of weak dispersive feedback strength of 0.35 (first row) and strong dispersive feedback strength of 1.60 (second row). Figure 3(a) depicts the reflection spectrum and group delay spectrum of CFBG (black curves), as well as the optical spectrum of laser chaos (blue curve) under the weak dispersive feedback. From this figure, it can be seen that the central wavelength of chaotic laser is 1549.72 nm which is redshifted due to the antiguidance effect of light feedback [36], and the optical spectrum is broadened. The corresponding RF spectrum is shown in Fig. 3(b). As can be seen, the energy of RF spectrum covers a wide frequency range of about 30 GHz. However, the energy locates mainly nearby the laser relaxation oscillation frequency (6 GHz) which dominates the RF spectrum, yielding a nonuniform spectrum with a 3-dB bandwidth of 8 GHz. Here, the bandwidth is defined as a RF spectrum width in which the power difference between the spectrum peak and other components is smaller than 3 dB. By contrast, in the scenario of strong dispersive feedback, the central wavelength of chaotic laser is redshifted to 1549.86 nm and the optical spectrum is better broadened, as shown in Fig. 3(c). More interestingly, as shown in Fig. 3(d), the domination of laser relaxation oscillation frequency is removed and more high-frequency components are introduced. It makes the energy of RF spectrum distribute uniformly yielding a 3-dB bandwidth of 24 GHz which is three times the bandwidth in the scenario

Fig. 2. Temporal waveforms and auto-correlation functions (ACFs) of laser chaos in the scenarios of (a), (b) weak dispersive feedback strength of 0.35; and (c), (d) strong dispersive feedback strength of 1.60.

Fig. 3. Optical spectra and RF spectra of laser chaos (blue curves) in the scenarios of (a), (b) weak dispersive feedback strength of 0.35; and (c), (d) strong dispersive feedback strength of 1.60. The black curves denote the reflection spectrum and group delay spectrum of CFBG. BW denotes bandwidth in short.

of weak feedback.

This phenomenon of bandwidth enhancement can be explained as follows. As shown by the black curves in Fig. 3(c), the dispersion of CFBG gives rise to frequency-dependent group delays and induces irregular separations to the external-cavity modes coming from the feedback light [34]. These irregular external-cavity modes return into the laser cavity and beat with the internal modes. The beating will convert chaotic phase dynamics with wide and flat spectrum into the intensity dynamics [25, 26], which stimulates more high-frequency oscillations widening and flattening the RF spectrum. Note that, the beating in our proposed method still takes place in the laser cavity, and thus the RF spectrum in low-frequency band is not as uniform as that in the high-frequency band. This mechanism of bandwidth enhancement is somewhat similar with that of optical injection-induced bandwidth enhancement [17].

Fig. 4. 3-dB chaos bandwidth as a function of (a) dispersive feedback strength of CFBG; and (b) wavelength detuning of laser and CFBG.

For the laser with conventional external mirror feedback, the bandwidth can also be slightly enhanced in the scenario of strong feedback. But, the domination of laser relaxation oscillation cannot be removed and the RF spectrum cannot be flattened [32]. Moreover, the bandwidth enhancement of CFBG feedback also shows a better performance compared with that of conventional FBG filtering which only widens and flattens the RF spectrum below the relaxation oscillation frequency [31].

Having confirmed the efficacy of the approach in generating the wideband and flat-spectrum chaos, we finally pay attention to the effects of dispersive feedback strength and wavelength detuning of laser and CFBG on the 3-dB bandwidth. In experiment, we examined the effects of dispersive feedback strength with a fixed wavelength detuning of -0.12 nm which is defined as the difference between the central wavelengths of free-running laser and CFBG. As shown in Fig. 4(a), the 3-dB chaos bandwidth increases with gradually reduced rate for increasing the dispersive feedback strength. As the feedback strength increases to 1.60, the 3-dB bandwidth reaches 24 GHz and keeps stable around it with further increasing the feedback strength. This means 1.60 is a critical value of strong dispersive feedback to yield the largest bandwidth enhancement, caused by the beating of dispersion-induced irregular external-cavity modes and the internal modes of laser. It is noted that, in the scenario of weak feedback strength, the irregular external-cavity modes induced by the dispersion also exist, but the weak feedback strength cannot support beating adequately. This is the same as optical injection-induced bandwidth enhancement for which a strong injection strength is required [22]. It also indicates that the EDFA is indispensable in the feedback loop to form active feedback providing enough power to satisfy the requirement of strong feedback, though it is not the origin of physical mechanism for bandwidth enhancement. In addition, the reason that the bandwidth cannot be further enhanced while reaching about 24 GHz is that the components of external-cavity modes are limited by the width of CFBG's reflection spectrum as shown in Fig. 3(c). Furthermore, we studied the effects of wavelength detuning with a fixed strong dispersive feedback strength of 1.60. For this study, the central wavelength of CFBG is fixed at 1549.76 nm and that of free-running laser is varied. As shown in Fig. 4(b), a 3-dB bandwidth of about 24 GHz can be always achieved when the wavelength detuning is in a range of -0.16 nm— -0.12 nm. It is noted that, the detuning range above mentioned assures that the main components of dispersion-induced irregular external-cavity modes beat with the internal modes of laser in the scenario of strong dispersive feedback, and thus the bandwidth can be guaranteed. While, outside this range, the main components of irregular external-cavity modes will be filtered partially degrading the effect of beating-induced bandwidth enhancement, and thus the bandwidth reduces.

4. Conclusions

In conclusion, a method of generating wideband and flat-spectrum chaos using a semiconductor laser subject to strong dispersive light feedback from a CFBG is proposed and experimentally demonstrated. Effects of the dispersive feedback strength and the wavelength detuning between the laser and the CFBG on the chaos bandwidth are investigated. Results show that, laser chaos with a 3-dB bandwidth of 24 GHz can be obtained. This proposed method has a simple device configuration with

the possibility of photonic integration and chaos synchronization, which paves the way of increasing the rates of laser chaos-based secure communication, random number generation, and key distribution.

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