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Generation of the non-periodic and delay-signature-free chaotic light

Yun-Cai WANG, An-Bang WANG, and Tong Zhao

The Key Lab. of Advanced Transducers & Intelligent Control System, Ministry of Education
College of Physics & Optoelectronics, Taiyuan University of Technology
No.79 West Yingze Street, Taiyuan, 030024, China
Email: wangyc@tyut.edu.cn, wanganbang@tyut.edu.cn

Abstract– External cavity semiconductor laser (ECSL) is becoming the most common chaotic light source due to its simple and integratable configuration. However, the round trip in feedback cavity with fixed delay makes the chaotic light periodic and reduces complexity. In this paper, we propose and demonstrate experimentally a novel optical feedback scheme to generate non-periodic chaotic light. Unlike the fixed time-delay feedback in ECSL, the proposed method utilizes the backscattering light from a fiber as feedback into semiconductor laser. Such a feedback is a kind of randomly distributed feedback along the fiber, and therefore its 'time-delay' is no longer a fixed value. Our results show that the proposed feedback method can obtain delay-signature-free chaotic light, which is very useful for the security of chaos encryption system and the generation of fast truly random numbers.

1. Introduction

Optical chaos in semiconductor lasers has proven to be broadband beyond several GHz [1, 2], and therefore has significant applications in high-speed chaos-based secure communication [3] and physical random number generation [4-6]. External cavity semiconductor laser (ECSL) that consists of a laser and an external mirror supplying optical feedback, is a particularly interesting source of chaotic light because of its simple structure and high-dimension dynamics. However, its chaotic output light usually retains obvious external-cavity delay signature [7] which makes the chaotic light periodic and degrades the performance in encryption applications.

In optical chaos communications, data information is encrypted by chaotic carrier from a transmitter ECSL and decrypted at the receiving end by chaos synchronization [3]. The security relies on the parameters of transmitting ECSL. The length of external cavity, i.e. feedback delay time is a vital parameter, because if it is cracked, the delay systems are faced with the risk of computational identification by eavesdropper through reconstructing phase space [8,9]. Unfortunately, it has been reported that the external-cavity delay signature can be readily extracted just from the intensity time series of ECSL by mathematic methods, such as and autocorrelation function (ACF), mutual information (MI) [10], and spectrum analysis [11].

In another burgeoning field, fast physical random number generation, ECSL is used as the source of physical entropy [4-6]. However, the delay-signature seriously affects the randomness and complexity of the chaotic light. The appearance of periodicity induced by external cavity limits the random number generation. For example, the sampling interval cannot equal the delay time [4], and some post processing is needed to eliminate the repeatability of the generated random number which inherits from the periodicity of chaotic ECSL output [6,12].

Therefore, a lot of efforts are devoted to suppress the periodicity in chaotic ECSL, i.e., the delay signature [7, 13-15]. Rontani *et al*. pointed out that the time delay identification will become extremely difficult, with a careful choice of parameters, by separating or closing the time delay and the relaxation oscillation period with low feedback rates [7], [13]. Other researchers proposed that adding another external cavity can suppress time delay signature of ECSL in two situations: one is that the two external cavities have rough equal lengths and feedback power ratios, and the other is that one cavity length is about half of another external cavity [14],[15]. However, these methods cannot completely eliminate the delay signature because the chaotic signal series is nearly identically repeated at the round trip time of external cavities. Nguimdo *et al*. found that the time delay can be identified by means of ACF and MI even when the time delay close to the relaxation oscillation period with low feedback rates [16]. Soriano *et al*. proposed permutation-information-theory approach to recover the time delay in systems with low feedback rate or high nonlinearity [17]. Our recent work [18] has revealed that the delay signature of ECSL with fixed feedback delays cannot be concealed.

In this paper, we present a novel feedback scheme to generate non-periodic chaotic light. Unlike the fixed time-delay feedback in ECSL, the proposed method utilizes the backscattering light from a fiber as feedback into semiconductor laser.

2. Experimental setup

Figure 1 shows the experimental setup of the proposed randomly distributed feedback to a laser diode. The laser used is a 1.55-um distributed feedback (DFB) laser without inner isolator. A proportion of its output is launched into a standard single mode fiber after amplified

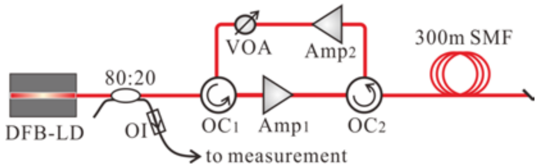

Fig. 1. Experimental setup. OC: optical circulator; Amp: erbium-doped fiber amplifier; VOA: variable optical attenuator; SMF: single mode fiber; OI: optical isolator.

by Amp1. The back scattered light along the fiber is injected into the DFB laser cavity, through the path consisting of OC2, amplifier 2, VOA and OC1. The amplifier and VOA are used to adjust the feedback strength. A polarization controller is used to match the polarization of feedback light with the laser. Note the end of the single mode fiber is beveled to avoid reflection.

In experiments, the DFB laser operating at 1553.9nm was biased at 1.5 times threshold. Its static output was about 0.2dBm with relaxation oscillation frequency of about 4GHz. In the feedback path, the scattering fiber was about 300m long, and the rest part was about 106m.

For comparison, we also studied the output of the DFB laser with optical feedback from an external fiber mirror. The bias current and wavelength of the laser remain unchanged. The external cavity length is about 107m of the fixed delay feedback. The chaotic output was measured by a real-time oscilloscope (LeCory SDA806Zi-A, 6GHz bandwidth, 40Gs/s sampling rate) and RF spectrum analyzer (AgilentN9020A).

3. Analysis Methods

In order to verify whether the feedback chaotic laser system is free of delay signature or not, we use two estimators. One is the ACF and the other is local RF spectrum [11].

The normalized ACF of a chaotic signal $P(t)$ is expressed as

$$C(\tau)=\frac{E\{P(t)P(t+\tau)\}}{[E\{P^2(t)\}E\{P^2(t+\tau)\}]^{1/2}}$$

Where, E denotes mathematic expectation. When lag $\tau=0$, C=1. If $P(t)$ has periodicity although implicit, the ACF will reach a maximum when lag τ equals to the period value.

4. Experimental Results

In order to compare the proposed method and the conventional ECSL, we first show an example of the output from ECSL. We note that, the delay signature is identified by the side-lobe of ACF trace of chaotic waveform, and the stronger the feedback light, the higher the side lobe [7]. Therefore, we choose an output of the ECSL obtained with strong feedback level of about -5dB. The trace of ACF is plotted in Fig. 2 with black curve. It clearly shows a side-lobe locating at 533.125ns which

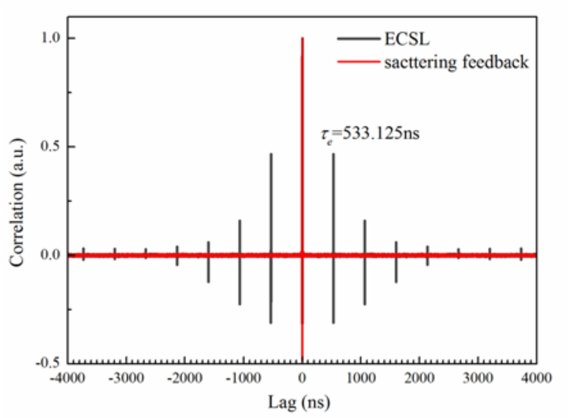

Fig. 2. Autocorrelation traces of chaotic outputs of ECSL (back) and scattering feedback laser (red). The feedback strength is -5dB.

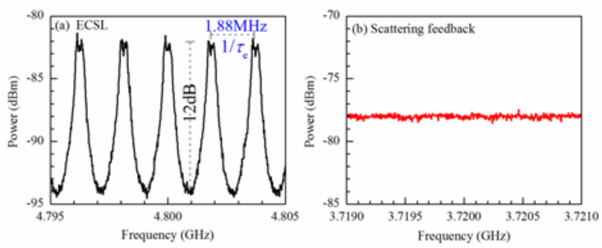

Fig. 3. Local RF spectra of chaotic outputs of ECSL (back) and scattering feedback laser (red). RBW: 100kHz; VBW: 10kHz, Sweeping time: 300ms.

indicates the external cavity feedback delay τ_e. Due to the high feedback level, the side-lobe height is near to the half of the main peak at zero lag. In addition, there are several harmonic peaks locating at $2\tau_e$, $3\tau_e$, $4\tau_e$, and so on.

By using the same strong feedback of -5dB, we experimentally obtained a chaotic light output from the laser with scattering feedback. Its autocorrelation trace is plotted in Fig. 2 with red line. Note that, in our experimental configuration, the feedback light comes from the scattering of the fiber. Therefore, if there were some side-lobes, they should locate in the fiber, i.e., in the range from 106 to 706m. The correlation trace clearly shows that no any peak appears on the trace in the lag range of 530 ~3530ns corresponding to the scattering fiber.

Further, we show the local RF spectra of the two outputs in Fig. 3. Figure 3(a) plots the RF spectra in range of 4.795~4.805GHz with span of 10MHz. Obviously, the spectrum exhibits a modulated profile. The peak interval is about 1.88MHz that equals to the reciprocal of cavity delay τ_e. Note $1/\tau_e$ is the so-called external cavity frequency. Actually, the frequencies of peaks are the integral multiple of the external cavity frequency. Benefiting from the long-time, low-noise and high-resolution sweeping frequency measurement of RF spectrum analyzer, the spectrum method can find the

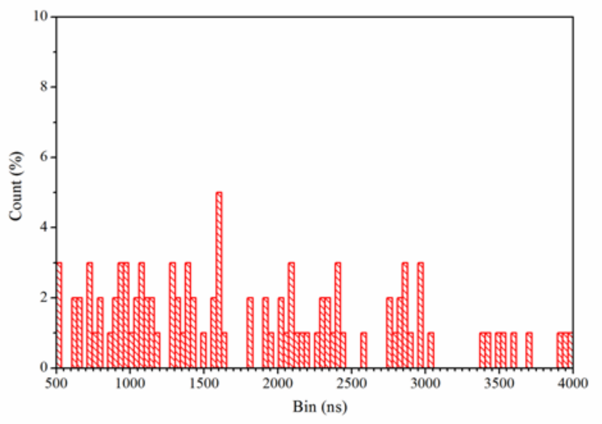

Fig. 4. Histogram of ACF maximum in time window 500-4000ns. The total number of sampled data is 100.

delay signature in some scenarios that are hardly identified by using ACF method [18].

Interestingly, the spectrum of the laser with scattering feedback has no any modulation profile that can indicate delay signature, as shown in Fig. 3(b). It should be mentioned that, the delay of the scattering fiber is distributed between 530 and 3530ns, therefore the 'cavity frequency' ranges from 0.283 to 1.887MHz. To resolve the minimum and cover the maximum interval, we set the resolution bandwidth of the used RF spectrum analyzer as 100kHz with sufficient sweeping time of 300ms. Note the video bandwidth was set as 10kHz. Seen from Fig. 3(b), the local spectrum in frequency band from 3.719 to 3.721GHz with 2MHz span is very flat without any periodic fluctuation. The random fluctuation of the spectrum is only in range of ±0.3dB. Therefore, both the autocorrelation trace and the local fine spectrum cannot find any delay signature like that exists in the chaotic output of ECSL.

Furthermore, we experimentally recorded 100 temporal waveforms of the chaotic state shown with red line in Fig. 2 and calculated their ACF traces. The corresponding maximum peaks of the ACFs in time window of 500~4000ns are counted within 100 time bins. The histogram is shown in Fig. 4. It can be found, the distribution of these peaks is nearly uniform unlike that the ECSL's ACF has a position-fixed side-lobe. This means the chaos in laser induced by the proposed scattering feedback has no delay signature, and therefore is non-periodic.

5. Conclusions

We propose a novel optical feedback using backscattering light to induce non-periodic chaos in semiconductor laser and demonstrate it experimentally. Unlike the fixed time-delay feedback in ECSL, such a feedback is a kind of randomly distributed feedback along the fiber, and therefore its 'time-delay' is no longer a fixed value. Our results show that the proposed feedback method can obtain delay-signature-free chaotic light, which is very useful for enhancing the security of chaos encryption system and the randomness of chaos-based fast true random numbers.

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