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Time-delay signature concealed broadband gain-coupled chaotic laser with fiber random grating induced distributed feedback

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HIGHLIGHTS

- A 7.53 GHz bandwidth chaotic laser system is achieved without time-delay signature.
- The fiber random grating feedback effectively conceals the time-delay signature.
- Laser injection is adopted to enhance the bandwidth of the chaotic laser.
- The chaotic laser can be used for random number generations and other applications.

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ABSTRACT

A broadband chaotic laser with a flat power spectrum extending up to ~7.53 GHz is achieved by injecting continuous wave laser light into a chaotic diode laser perturbed by fiber random grating induced distributed feedback, which forms a gain-coupled chaotic laser system. More than triple bandwidth enhancement is realized with appropriate frequency detuning between the master and slave lasers. Unlike normal chaotic lasers, the output from such a broadband chaotic laser is free from time-delay signature, which can be potentially applied for practical random number generations and will find useful applications in the fields of information security and computation systems.

1. Introduction

Broadband chaotic semiconductor lasers have been extensively studied during the past several decades for their valuable applications in secure communications [1–5], random number generations [6–12], chaotic lidar [13,14], compressive sensing [15], and time domain reflectometry [16,17]. It is well-known that semiconductor lasers exhibit a rich variety of lasing dynamics with external perturbations such as optical feedback, laser injection, current modulation, and optoelectronic feedback [18–20]. Among these lasing dynamics, chaotic oscillation in semiconductor lasers has drawn intensive attentions, which has been realized by various perturbation techniques. Perturbations can overcome the limited bandwidth of the intrinsic chaotic intensity oscillations in semiconductor lasers dominated by laser relaxation oscillation and significantly broaden the chaotic bandwidth of the laser output. Among the perturbation techniques, the passive optical feedback and active laser injection configurations are the most effective and simplest schemes for chaotic oscillation generation and bandwidth enhancement [21]. However, the optical feedback based chaotic laser systems often suffer from the time-delay signature (TDS) in chaotic outputs, which exhibits as periodicities in output time series. This is induced by the photon round-trip in the external cavity formed by the optical feedback. The TDS in chaos communications will allow eavesdroppers to crack the encryption systems and deteriorate the security of the communication systems. Various feedback configurations have been proposed and investigated to overcome the TDS in chaotic laser output, including single mirror feedback [22], dual-path feedback from double mirrors [23], fiber Bragg grating (FBG) feedback [24,25], feedback with cascaded coupled laser injection [26], on-chip integrated optical feedback [27] and so on. In FBG feedback configuration [24,25], the laser frequency has to be tuned to edges of the main lobe of FBG reflection spectrum, which leads to a significant power loss in reflection, weakening the feedback strength to the semiconductor laser. The FBG spectrum that is sensitive to environmental disturbances will also bring

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instability to the detuning frequency and compromise the TDS suppression. Furthermore, the broadening of the chaotic bandwidth based on only the optical feedback perturbation is still limited by the intrinsic relaxation oscillation of the single semiconductor laser. Thus it cannot meet the high-speed requirement for the current fast chaos communication systems. Laser injection technique has also been combined with the optical feedback technique to further enhance the chaotic bandwidth [28,29], however, TDS still remains in the previously reported works and therefore the proposed chaotic laser systems cannot be used for realizing truly random bit generations.

In this paper, we experimentally demonstrate a broadband gain-coupled chaotic laser system with random distributed feedback from a fiber random grating and additional laser injection. The TDS in the output signal of the chaotic laser is completely suppressed thanks to the fiber random grating feedback, which significantly complicates the external feedback cavity features and thus the chaotic laser dynamics. The random distributed feedback erases the original cavity modes in both slave and master lasers, and creates larger numbers of random cavity modes in the new chaotic laser system due to the randomness feature of the distributed feedback. As a result, different chaotic lasing dynamics are achieved comparing with normal chaotic laser. Compared to the work where a 10 km-long single mode fiber is used to provide random distributed feedback for TDS concealment [30], the fiber random grating with length in the order of centimeters has more advantages such as a more compact size and readily to be packaged and integrated. The cumbersome long single mode fiber is hard to be packaged and more easily to be disturbed by external disturbances, which may result in compromise performances for the concealment of TDS. While the fiber random grating with small footprint can be easily well packaged and thus guarantee a more stable performance. The proposed broadband chaotic laser is believed to be an excellent candidate for useful applications in secure communications, random number generations and optical sensing.

2. Experiments and results

The experimental configuration of the proposed broadband chaotic laser system is shown in Fig. 1(a). Two distributed feedback coaxial laser diodes (LDs) are used as light sources, one as slave LD and the other as master LD. The output power of the LD as a function of the driving current is shown in Fig. 1(b). The measured threshold driving current is about 6 mA, above which the LD output power increases linearly with the driving current. The optical spectrum of the LD is measured as shown in Fig. 1(c), where the center wavelength is located around 1548 nm. The spectral peak of the LD could be adjusted through temperature control. Light from the slave LD passing through Circulator 1 (CIR 1) was first amplified by an Erbium-doped fiber amplifier (EDFA) and Polarization Controller 1 (PC 1) was used to adjust the state of polarization (SOP) of the intra-cavity light. The amplified light was then sent through the Circulator 2 (CIR 2) to be scattered back by a fiber random grating. The randomly backscattered light was passed through Attenuator 1 (Atn 1) and guided back to the slave LD after being combined with the light from the master LD. The fiber random grating sample was fabricated through the plane-by-plane inscription without phase control [31]. A total of ~25,000 index modified planes with random spatial interval from 0 to 3.5 μm and random index modulations were introduced, which act as enhanced Rayleigh scattering centers randomly distributed along the 2.5 cm long standard single mode fiber. The enlarged schematic image in Fig. 1(a) exhibits that multiple interferences occur along the fiber random grating with reflections from different spots. The reflectivity of the fiber random grating was measured to be ~0.001 over a broad spectral range from 1540 nm to 1560 nm. It is worth mentioning that the transmission loss of the random grating sample was controlled to be less than 3 dB, which enables the direct detection of the chaotic light at the output end of the grating sample. A 12 GHz bandwidth photodetector (1544-A, New Focus) was used to monitor the chaotic laser output, which was afterwards digitized by an oscilloscope (DS081204B, Agilent) with a bandwidth of 12 GHz. An optical spectral analyzer (AQ6375, Yokogawa) with a resolution of 0.02 nm and an electrical spectral analyzer (E4446A, Agilent) with a resolution bandwidth ranging from 1 Hz to 6 MHz were also used to characterize the laser output spectrum.

In experiments, the impact of random distributed feedback from the fiber random grating on the chaotic output of the slave LD was firstly investigated. To this end, the master LD was disconnected from injecting laser output into the slave LD. The driving current for the slave LD was set to around 6.5 mA, which is slightly above the threshold value. With this driving current, the slave LD emits light with a power less than 100 μW. After being amplified by the EDFA, the intra-cavity light is randomly reflected by the large numbers of scattering centers along the fiber random grating. During the experiments, the fiber random grating was put into a soundproof box to be isolated from environmental perturbations. Since the backscattering from the fiber random grating is sensitive to the SOP of the input light [32], the SOP of the intra-cavity light is adjusted by PC 1 to optimize the chaotic laser bandwidth. Fig. 2 shows the experimentally obtained evolution of the optical spectra and radio-frequency spectra of the chaotic slave LD when only the random distributed feedback from the fiber random grating is available. The delay length in the chaotic laser system is

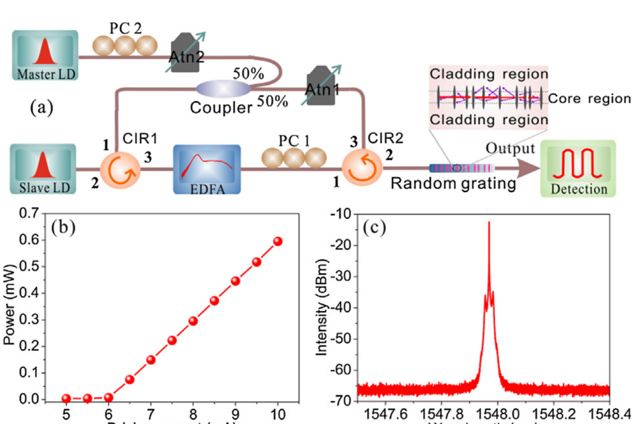

Fig. 1. (a) Experimental setup of the proposed broadband chaotic laser system. Atn: Attenuator, CIR: Circulator, EDFA: Erbium-doped fiber amplifier, LD: Laser diode, PC: Polarization controller. (b) Output power of laser diode as a function of driving current. (c) Optical spectrum of the laser diode output.

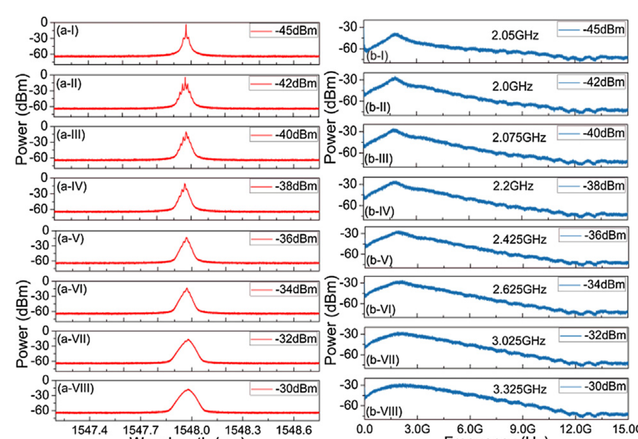

Fig. 2. Experimentally obtained evolution of the optical spectra (a) and radio-frequency spectra (b) of the slave LD only subjected to the random distributed feedback from the fiber random grating with feedback strengths ranging from −45 dBm to −30 dBm.