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# Photonic integrated chaotic semiconductor laser

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**Abstract–** We designed and fabricated a wavelength-tunable chaotic semiconductor laser chip. The chip consists of a gain section, a distributed Bragg reflector grating section, a semiconductor optical amplifier section, and a phase section. With the optical feedback from the reflective facet of the phase section, and the mode-beating of composite cavities, the chip emits chaotic laser. By adjusting the current of DBR grating, the wavelength can be tuned in a range of 13.4 nm, and the central wavelength can be fine-tuned by adjusting the current of the phase section. To further expand the bandwidth of the chip, an optical feedback loop is applied. By stimulating the nonlinear frequency mixing in the laser cavity, the chaos bandwidth is expanded to 33.6 GHz. Furthermore, the effect of feedback optical power on the bandwidth is investigated. The results show that the wide power spectrum of chaotic laser is available in a large wavelength range from 1556.44 nm to 1566.42 nm. This work explores a broadband and wavelength-tunable chaotic semiconductor laser for the wavelength division multiplexing to enlarge the capacity in chaotic secure optical communications.

## 1. Introduction

Chaotic laser has been widely used in the field of secure optical communications [1-2], distributed optical fiber sensing [3-5], random number generation [6], optical time domain reflection (OTDR) [7] and so on. Due to the hardware encryption based on physical layer, the chaos communications have strong security performance [8]. With the rapid growth of data, the capacity of optical fiber communications has expanded largely. In order to be compatible with optical fiber communications, new technologies in chaos communications need being developed to improve the transmission rate and capacity. Chaotic wavelength division multiplexing (WDM) is an effective solution to enlarge the capacity of chaos communications. As a crucial component, a chaotic laser with a large range of wavelength tuning is necessary. At present, wavelength tunable chaotic lasers are mainly realized by the filtering of multi-longitudinal mode laser diode.

However, the improvement of capacity in chaotic secure optical communications relies not only on the WDM technology to achieve a multi-channel transmission [12], but also on the bandwidth enhancement of chaotic laser at each wavelength channel to enlarge the transmission rates and capacity [13]. Limited by the relaxation oscillation frequency, the chaos bandwidth generated in the method of optical feedback is only several GHz. Therefore, the researches on broadband chaos generation have been widely studied. On the one hand, numerous researches adopt optical injection. It has been proved that single beam optical injection [14-15], dual-wavelength optical injection [16-17], mutual injection [18-19] and cascade optical injection [20] can expand chaotic laser bandwidth largely by introducing additional freedom degree. But schemes above are multiple parameters and require fine adjustment, and the lasers are easy to be injected locked. On the other hand, methods based on optical feedback have also been studied. In the optical feedback structure, a semiconductor laser subject to asymmetric dual-path optical feedback [21], phase-conjugate feedback [22], delay-interfered self-phase-modulated feedback [23], or the feedback from parallel coupling ring resonators [24] have been proved to generate broadband chaotic laser. In 2015, Zhao *et al*. proposed a broadband chaotic laser using a monolithically integrated amplified feedback laser (AFL) with optical feedback [25]. The chip can output broadband chaos under optical feedback due to the dual-mode in the AFL. Nevertheless, whether optical injection or optical feedback, the methods above adopt DFB laser diode as the light source, whose wavelength is un-adjustable in a large range [26]. This restrains the application of broadband chaotic laser in WDM technology.

In this paper, we first propose a wavelength-tunable chaotic semiconductor laser chip, which is composed of a gain section, a distributed Bragg reflector (DBR) section, an optical amplifier section, and a phase section. Furthermore, we propose a method to expand the bandwidth of the wavelength-tunable chaotic laser which consists of a wavelength-tunable chaotic laser chip and an optical feedback loop.

## 2. Researches

### 2.1. Wavelength-tunable monolithically integrated chaotic semiconductor laser

The schematic diagram of the monolithically integrated chaotic semiconductor laser chip is shown in Fig. 1. The chip consists of a gain section, a DBR section, a semiconductor optical amplifier (SOA) section, and a

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phase section. Their lengths are 297 μm, 147 μm, 347 μm, and 72 μm, respectively. The reflectivity ratio of the grating is 0.3. Both sides of the chip are cleavage fracture, whose reflectivity ratio is 0.32. The laser emits from the right facet of the gain section. In the chaotic laser chip, the DBR grating section and the right facet of gain section constitute a resonant cavity. When the current of gain section is biased above threshold, the chip emits laser, which is amplified by the SOA section, and then reflected by the facet of phase section. The feedback light provides optical perturbation to the gain section, which disturb the balance of photon and carrier. As a result, the chip output chaotic laser. Moreover, by tuning the bias current of the DBR section, the wavelength tuning can be achieved due to the adjustment of the Bragg wavelength.

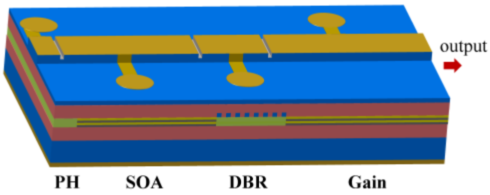


Fig. 1. Schematic diagram of chaotic laser chip. Gain: gain section, DBR: distributed Bragg reflector section, SOA: semiconductor optical amplifier section, PH: phase section.

The DBR grating is designed to tune the chaotic laser wavelength by mode selection. The Bragg wavelength of the DBR grating is adjusted with the variation of the biased current of DBR section. Figure 2(a) shows the wavelength tuning for the chaotic laser through tuning DBR section biased current, while $I_{gain}$ is fixed at 60.0 mA, and $I_{SOA}$ is fixed at 0.4 mA to compensate the loss of the active cavity. By tuning the DBR section biased current, the longitudinal mode closest to the Bragg wavelength is selected, and the peak wavelength of the chip moves to the shorter wavelength. As shown in Fig. 2(a), the wavelength is tuned from 1551.4 nm to 1564.8 nm, the tuning range is 13.4 nm, and the wavelength tuning interval is 1.1 nm. The tuning interval depends on the longitudinal mode interval of the resonant cavity, which is determined by the resonant cavity length.

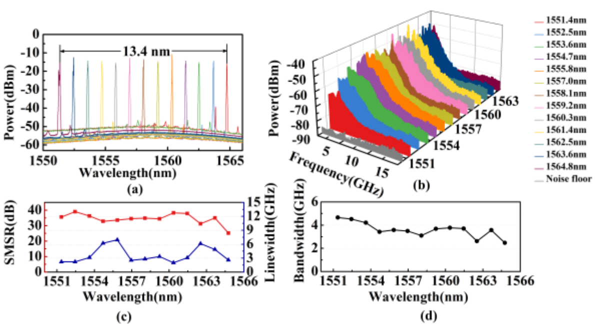


Fig. 2. Wavelength-tunable chaotic laser, (a) optical spectra, (b) the corresponding power spectra, (c) the corresponding side-mode suppression ratio and linewidth, (d) standard bandwidth. Note: Igain=60.0 mA, ISOA=0.4 mA, Iphase=0.0 mA, from 1564.8 nm to 1551.4 nm, the biased current of the DBR section is 0.1 mA, 0.4 mA, 1.0 mA, 1.6 mA, 2.4 mA, 3.6 mA, 5.5 mA, 7.6 mA, 10.7 mA, 14.5 mA, 20.6 mA, 29.1 mA, 40.4 mA, respectively.

The optical spectra are more thoroughly illustrated in Fig. 2(c) as the wavelength is tuned. The side mode suppression ratio (SMSR), which indicates the level of the interference of the side-mode, is plotted in the Fig. 2 (c) red dotted line. It fluctuates between 25.1 dB to 39.2 dB, meaning single-mode output. The -3dB linewidth at each peak wavelength is calculated in the Fig. 2 (c) blue dotted line. The -3dB linewidth is between 2.01 GHz and 6.95 GHz, indicating that the optical spectrum is broadened at each wavelength. Figure 2 (b) shows the power spectrum at each wavelength. The relaxation oscillation frequency of the gain section interacts with the resonant frequency of the SOA active cavity, so that new frequency components are stimulated and the power spectrum of each wavelength rises on the frequency of 0~15 GHz. The standard bandwidth of chaotic laser power spectrum at each wavelength is calculated in Fig. 2 (d), which is between 2.5 GHz and 4.7 GHz. All in all, by adjusting the current of the DBR section, the chaotic laser with broadband power spectrum and broad optical spectrum can be available in a large wavelength range.

### 2.2. Broadband chaos generation utilizing a wavelength-tunable monolithically integrated chaotic semiconductor laser subject to optical feedback

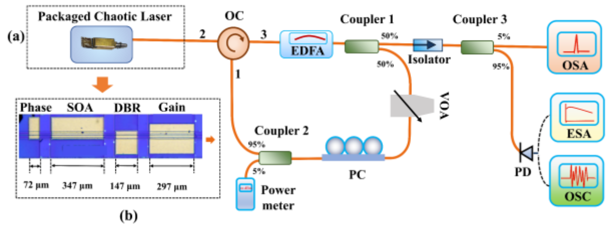


Fig. 3. (a) Experimental setup of ring optical feedback based on the chaotic laser chip, (b) Schematic diagram of the chaotic semiconductor laser chip. OC, optical circulator, EDFA, Erbium-doped fiber amplifier; PC, polarization controller; VOA, variable optical attenuator; OSA, optical spectrum analyzer; ESA, electric spectrum analyzer; OSC, oscilloscope; PD, photo-detector.

The experimental setup is shown in Fig. 3(a), it includes a wavelength-tunable monolithically integrated CSL and an optical feedback loop. As the chip emits chaotic laser, the light passing through the optical circulator (OC) is amplified by an Erbium-doped fiber amplifier (EDFA), and then divided into two parts via the coupler 1. One part is used to monitor the chaotic laser output, the other part passes through a variable optical attenuator (VOA) and a polarization controller (PC), and then is fed back to the chip via OC. The feedback strength and the polarization state can be adjusted by the VOA and the PC. A smaller part of the light was separated via the coupler 2 to measure the feedback optical power. In the experiment, the output used for measurement is divided into two parts through a 95:5 fiber coupler 3: the smaller part is monitored by an optical spectrum analyzer (OSA, Yokogawa AQ6370D, 0.02 nm resolution), the other part is sent to a photo-detector (PD, Finisar XPDV2120R-VF-FP, 50 GHz bandwidth), and finally digitized by an electric spectrum analyzer (ESA, Rohde and Schwarz FSW50, 50 GHz bandwidth) or a real-time oscilloscope (OSC, LECROYWP804HD, 8 GHz bandwidth, 20 GS/s sampling rate) , which are used to monitor power spectrum and time series.

The wavelength tuning of broadband chaotic laser is investigated by adjusting the bias current of the DBR section in the laser chip. Figure 4 presents optical spectrum, power spectrum, and standard bandwidth at each wavelength. As shown in Fig. 4(a), when the current of DBR section is 1.6mA, 2.6mA, 4.1mA, 6.0mA, 8.6mA, 12.4mA, 17.7mA, 25.5mA, 36.1mA, 50.4mA, respectively, the output of chaotic laser chip with optical feedback loop can be tuned at 10 wavelengths in the range from 1566.42 nm to 1556.44 nm. The tuning of the wavelength is discrete, and the tuning interval is around 1.00 nm. The wavelength tuning interval of the chaotic laser is determined by the length of the resonant cavity formed by the DBR grating and the reflected interface at the right end of the gain section. This F-P resonant cavity generates multiple longitudinal modes, and then the wavelength tuning is realized by mode selection through the DBR grating. Since the multiple longitudinal modes generated by the F-P resonant cavity are discrete, the wavelength tuning is discrete. The variation of the gain section current will slightly affect the tuning interval due to the effective refractive index variation of the gain section. However, the gain section current is controlled within a small range of variation, so the influence on the wavelength tuning interval is negligible. At each wavelength, by increasing the optical feedback power in the ring optical feedback structure, a broadband chaotic laser can be achieved. As shown in Fig. 4(b), all power spectra present broadband characteristics. The power spectra are lifted visibly compared to the noise floor, and they cover a frequency range of 0~50 GHz, indicating a broadband chaotic laser characteristic. In Fig. 4(c), the standard bandwidth of the power spectrum at each wavelength is calculated. When the wavelength is tuned from 1556.44 nm to 1564.36 nm, the standard bandwidth is above 25.0 GHz, and the maximum bandwidth can reach 33.6 GHz. It can be seen that by adding a simple optical feedback structure, the bandwidth of the chaotic laser can be greatly increased, and more importantly, the characteristics of the chaotic laser is stable in the wavelength range of 9.98 nm. However, the TDS value, defined by the peak value of autocorrelation function, is around 0.3 in Fig. 4(d). Especially, when the TDS value is 0.6 at the wavelength of 1566.42nm, the bandwidth of the chaotic laser decline dramatically, which verifies the stronger periodicity of the chaotic laser at 1566.42nm.

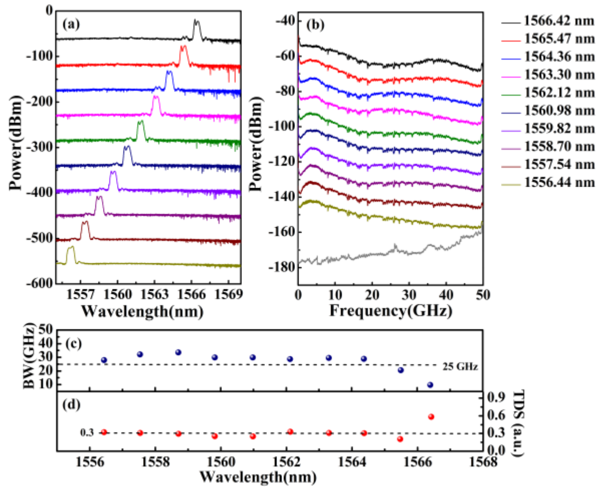


Fig. 4. Chaotic laser at different wavelengths when feedback optical power is 1.2mW, (a) optical spectra, (b) power spectra, (c) the standard bandwidth of chaotic lasers, (d) time delay signature of time series. BW: standard bandwidth, the gray line in (b) is the noise floor. TDS: time delay signature, which is defined by the peak value of the autocorrelation function.

## 3. Conclusions

In this paper, a four-segment chaotic semiconductor laser chip is proposed, fabricated, and investigated. The chip can generate the chaotic laser with bandwidth of 4.9 GHz. By controlling the Bragg wavelength of the DBR grating, the wavelength of chaotic laser can be tuned from 1551.4 nm to 1564.8 nm, whose wavelength-tuning range is 13.4 nm, and wavelength-tuning interval is 1.1nm. Furthermore, a method of generating broadband and wavelength-tunable chaotic laser is proposed and demonstrated. With ring optical feedback of the chaotic laser emitted by the monolithically integrated CSL, the maximum chaos bandwidth of the chip is expanded to 33.6 GHz. At each wavelength, the increase of the feedback optical strength can enhance the bandwidth of the chaotic laser. The results show that bandwidth of the chaotic laser is around 25.0 GHz when the wavelength is tuned from 1556.44 nm to 1566.42 nm at intervals of 1.00 nm. This method provides a broadband chaotic laser with a large wavelength tuning range for WDM technology to achieve large-capacity and high-speed chaos optical communications.

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