



## Chaos Bandwidth Enhancement of Fabry-Perot Laser Diode With Dual-Mode Continuous-Wave Optical Injection

Han, Hong; Zhang, Ming Jiang; Shore, K. Alan

### IEEE Journal of Quantum Electronics

Published: 01/06/2019

Peer reviewed version

[Cyswllt i'r cyhoeddiad / Link to publication](#)

*Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):*

Han, H., Zhang, M. J., & Shore, K. A. (2019). Chaos Bandwidth Enhancement of Fabry-Perot Laser Diode With Dual-Mode Continuous-Wave Optical Injection. *IEEE Journal of Quantum Electronics*, 55(3), [2000708 ].

#### Hawliau Cyffredinol / General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

#### Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

# Chaos Bandwidth Enhancement of Fabry-Pérot Laser Diode With Dual-Mode Continuous-Wave Optical Injection

Hong Han, Ming Jiang Zhang, K. Alan Shore, *Senior Member, IEEE*

**Abstract**—We show numerically that dual-mode continuous-wave optical injection into a Fabry-Pérot laser diode subject to optical feedback generates a chaos bandwidth which is four to six times that without optical injection. As a comparison, it is shown that single-mode optical injection can increase the chaos bandwidth threefold with careful choice of detuning. Any combination of dual-mode injection will further enhance the chaos bandwidth and especially for strong injection and over relatively large positive detuning ranges. Even when the bias current of the Fabry-Pérot laser diode is relatively low, the bandwidth of chaos can reach 35 GHz after dual-mode optical injection, which is six times that without optical injection. The enhanced bandwidth with dual-beam optical injection is in accordance with our previous experiments [25]. The present simulations provide detailed guidance on the choice of experimentally accessible parameters to generate chaotic signals with enhanced bandwidth by using single or dual-beam optical injection into a Fabry-Pérot laser diode with optical feedback.

**Index Terms**—Bandwidth enhancement, chaos, Fabry-Pérot laser, dual-mode optical injection, optical feedback.

## I. INTRODUCTION

CHAOTIC semiconductor lasers have been used in chaos radar [1]-[5], optical reflectometry [6]-[11], Brillouin optical correlation domain analysis [12], [13], physical random number generation [14]-[17], and chaos-based secure communication [18]-[21], where advantage has been taken of the broadband nature of optical chaos. A semiconductor laser with optical feedback, optoelectronic feedback or single-beam optical injection usually generates chaos with bandwidths around several GHz which limits the range resolution of chaotic lidar, the bit rate of random sequence generation and the transmission rate of optical chaos communications. To generate a broad spectrum of chaotic light, three combination methods

have been proposed including, optical feedback together with single-beam optical injection [22], [23], dual-beam optical injection [24], and optical feedback together with dual-beam optical injection [25], [26]. Takiguchi *et al.* numerically demonstrated that the bandwidth of single-mode semiconductor laser under optical feedback and single-beam optical injection is expanded roughly three times by strong optical injection, that is 8 GHz, compared with the bandwidth without injection (2.7 GHz) [22]. Wang *et al.* reported this three-times bandwidth enhancement could be obtained in experiments by adjusting the detuning of the injected light [23]. The behaviour of a semiconductor laser with dual-beam injection is numerically investigated by Qi *et al.*, where the bandwidth of chaos is improved to 24.02 GHz [24]. In 2011, our group experimentally realized a 32.4 GHz bandwidth chaos by using dual-wavelength continuous-wave (CW) optical injection of a Fabry-Pérot laser diode (FP-LD) with optical feedback [25]. By injecting dual chaotic optical into a single-mode semiconductor laser, Xiang *et al.* numerically obtained a broader bandwidth compared with single chaotic injection [26].

A much more complicated dynamics of semiconductor laser can be obtained by using dual-beam CW optical injection than those in single-beam optically injected semiconductor lasers, as has been studied in [27-30]. However, there attention was paid to single-mode semiconductor laser under dual-beam optical injection. In chaotic optical communication applications, multimode FP-LDs can be used as a wavelength converter [31], for demultiplexing the chaos carrier wave [32] and multiplexing the chaos carrier wave in physical security-enhanced wavelength division multiplexing chaos communication [33]. By using unidirectional optical injection, FP-LDs can realize 30 GHz 3dB modulation bandwidth, which is suitable for high-speed optical communication [34]. Our previous experiments indicate that enhanced bandwidth of the optical chaos can be obtained from a FP-LD with optical

Manuscript submitted September 7, 2018. This work was supported in part by the National Natural Science Foundation of China (61741512, 61527819, 61601319, 61731014, 61705160, 61475111), the International Science & Technology Cooperation Program of China (2014DFA50870), the Natural Science Foundation of Shanxi Province (201601D202043), the Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi (20171118), and the China Scholarship Council (201706935037).

H. Han is with the Key Laboratory of Advanced Transducers and Intelligent Control System, Ministry of Education, the College of Physics and Optoelectronics, the Taiyuan University of Technology, Taiyuan 030024,

China, and also with the School of Electronic Engineering, Bangor University, Wales, LL57 1UT, UK.

(email: hanhong@tyut.edu.cn)

M. J. Zhang is with the Key Laboratory of Advanced Transducers and Intelligent Control System, College of Physics and Optoelectronics, Ministry of Education, the Taiyuan University of Technology, Taiyuan 030024, China.

(email: zhangmingjiang@tyut.edu.cn)

K. Alan Shore is with the School of Electronic Engineering, Bangor University, Wales, LL571UT, UK.

(email: k.a.shore@bangor.ac.uk)

feedback by using dual-wavelength CW optical injection [25]. This broadband chaotic laser has potential for improving the bit rate of random sequence and the transmission rate of optical chaos communications. In 2016, Obaid *et al.* numerically calculated dual-beam CW optical injection FP-LD with optical feedback to gain a broad bandwidth chaos signal, where each injection wavelength has a positive detuning from the central mode of the FP-LD is injected [35]. Their approach appears to depend upon the inclusion of an optical amplifier whose role is analysed. Unfortunately the numerical model used in the work is neither described nor disclosed and it is thus problematic to make meaningful comparisons.

In this paper, we firstly investigate single-beam CW optical injection into a FP-LD with optical feedback, exciting different modes of the FP-LD to find the enhancement of chaos bandwidth for these modes. Then consideration is given to dual-mode CW optical injection where the effects of frequency detuning, combination of injection modes, injection strength as well as bias currents on enhancement of bandwidth are investigated in detail. Our numerical results are in accordance with previous experiments (ref. [25]) and provide guidance to enable the choice of experimentally accessible parameters to generate chaotic signals with enhanced bandwidth.

## II. THEORETICAL MODEL

Figure 1 shows the schematic of the proposed chaos bandwidth enhancement scheme by single-mode or dual-mode injection. A Fabry-Férot laser diode (FP-LD) subject to an external mirror feedback is used to generate the original chaos signal. 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 a 50/50 coupler. The wavelength of the DFB-LD is set close to one of the FP-LD's modes. This scheme is as same as the previous relevant experiment [25].

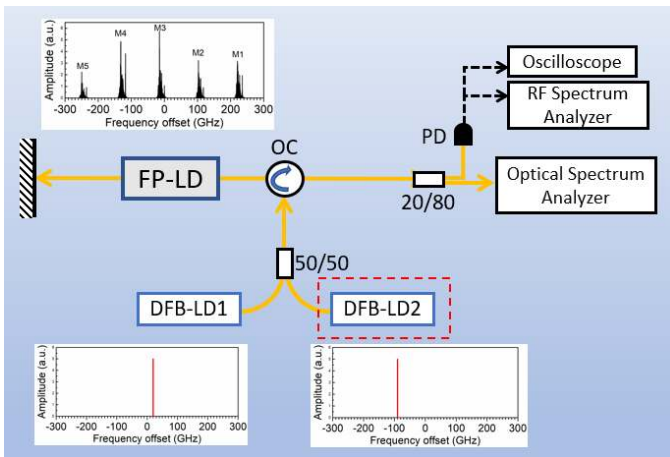


Fig 1. Schematic of enhanced bandwidth chaotic laser by single-mode or dual-mode injection

Numerical simulations are based on Lang-Kobayashi equations [36]. The rate equations for FP-LD is obtained by the developed Lang-Kobayashi equations where optical feedback and injection items are considered, as shown in eqs. (1) and (2).

$$\begin{aligned} \frac{dE_m(t)}{dt} = & \frac{1}{2}(1+i\alpha)[G_m(t)-\gamma_p]E_m(t) \\ & + k_f E_m(t-\tau_f)\exp(-i\omega_m\tau_f) \\ & + k_{mj1,2}E_{1,2}(t-\tau_{1,2})\exp(-i\omega_{1,2}\tau_{1,2})\exp(i\Delta\omega_{1,2}t) \end{aligned} \quad (1)$$

$$\frac{dN(t)}{dt} = \frac{I}{e} - \gamma_e N(t) - \sum_{m=1}^M G_m(t)|E_m(t)|^2 \quad (2)$$

where  $m$  denotes the mode number,  $M$  is the total numbers of FP-LD. In this paper we consider 5 modes, that is  $M=5$  with the central mode being designated by  $m_c=3$ .  $E(t)$  is the electric field amplitude which is normalized, therefore the output intensity is determined by  $P(t)=|E(t)|^2$ .  $N(t)$  is the carrier number in the cavity. The mode-dependent optical gain  $G_m(t)$  for FP-LD is defined as

$$G_m(t) = \frac{g(N(t)-N_0)}{1+s\sum_{m=1}^M |E_m(t)|^2} \left[ 1 - \left( \frac{(m_c-m)\Delta\omega_L}{\Delta\omega_g} \right)^2 \right] \quad (3)$$

The parabolic profile has a maximum centered at  $m_c$ th mode, corresponding the mode 3.  $\Delta\omega_L=2\pi/\tau_L$  is the longitudinal mode spacing (117 GHz), which is determined by the internal round-trip time  $\tau_L$ , and  $\Delta\omega_g$  is the gain width of laser material.

The Lang-Kobayashi equations for the DFB-LDs can be written as

$$\frac{dE_{1,2}(t)}{dt} = \frac{1}{2}(1+i\alpha) \left[ \frac{g(N_{1,2}(t)-N_0)}{1+s|E_{1,2}(t)|^2} - \gamma_p \right] E_{1,2}(t) \quad (4)$$

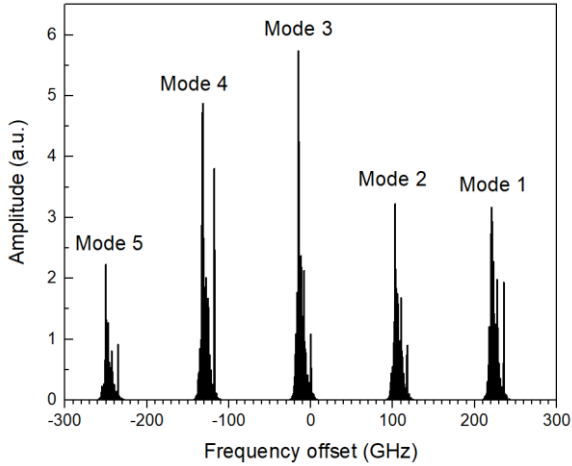
$$\frac{dN_{1,2}(t)}{dt} = \frac{I}{e} - \gamma_e N_{1,2}(t) - \frac{g(N_{1,2}(t)-N_0)}{1+s|E_{1,2}(t)|^2} |E_{1,2}(t)|^2 \quad (5)$$

where 1 and 2 denotes DFB-LD1 and DFB-LD2 with different central wavelengths,  $\alpha$  is the linewidth enhancement factor,  $\gamma_p$  is the photon decay rate,  $\gamma_e$  is the carrier decay rate,  $s$  is the saturation compression factor,  $g$  is the differential gain coefficient. For FP-LD in eq.(1), the angle frequency  $\omega_m$  can get by  $\omega_m = \omega_c + (m_c - m)\Delta\omega_L$ , the detuning frequency of between DFB-LD1 or DFB-LD2 and the injected mode of FP-LD is  $\Delta\omega_{1,2} = \omega_{1,2} - \omega_m$ . The model takes no account of multiwave mixing effects. In addition, no consideration is given to the effects of noise which would not be expected to impact the gross features of the dynamics. Here, we assume the devices are fabricated using the same material platform thus leading to identical material parameters of DFB-LDs and FP-LD as listed in Table 1, which mainly refer ref. [32, 33].

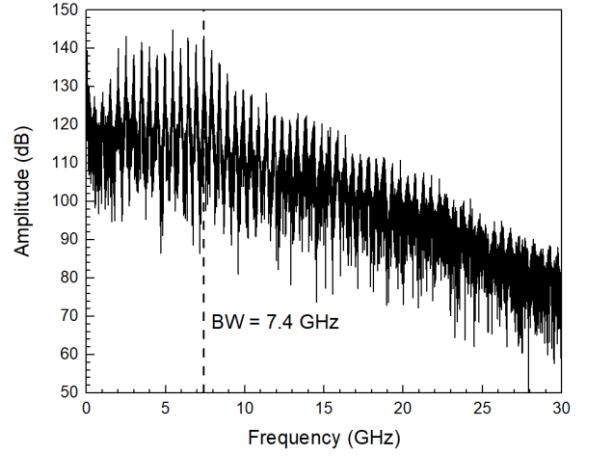
TABLE I  
SIMULATION PARAMETER VALUES[32,33]

Parameter	Symbol	Value
Linewidth enhancement factor	$\alpha$	3.5
Cavity decay rate	$\gamma_p$	$0.238 \text{ ps}^{-1}$
Carrier decay rate	$\gamma_e$	$0.621 \text{ ns}^{-1}$
Threshold current	$I_{th}$	19.8 mA
Internal round-trip time	$\tau_L$	8.5 ps
Material gain width	$\Delta\omega_g$	$2\pi \times 10 \text{ THz}$
Saturation coefficient	$s$	$1.0 \times 10^{-7}$
Differential gain	$g$	$3.2 \times 10^{-9} \text{ ps}^{-1}$
Transparency inversion	$N_0$	$1.25 \times 10^8$
Feedback level	$\kappa_f$	$30 \text{ ns}^{-1}$
Feedback time	$\tau_f$	2 ns
External Injection delay	$\tau_{1,2}$	0 ns

Figure 2 displays the optical and power/rf spectra of FP-LD with  $30 \text{ ns}^{-1}$  external cavity optical feedback. We term this state as the original chaotic state. In Fig. 2 (a), mode 5 to mode 1 are displayed from left to right, where the mode 3 is the central mode. Compared with the free running state each longitude mode of FP-LD is broadened and undergoes a red-shift resulted from the change of carrier density and many extended cavity modes are excited due to optical feedback. We use here a conventional definition of chaos bandwidth (BW) of chaotic signals as the frequency span between the DC and the frequency where 80% of the energy is contained [37]. The BW of the original chaotic laser is 7.4 GHz presented with dashed line in Fig. 2(b), when the bias current of FP-LD is  $2I_{th}$ .



(a)



(b)

Fig 2. Optical spectra (a) and rf spectra (b) of the original chaos light.  $I=2I_{th}$ ,  $k_f=30 \text{ ns}^{-1}$ , without injection BW is 7.4 GHz.

### III. SINGLE-MODE INJECTION

Single-mode optical injection initially makes the chaos bandwidth of the injected mode linearly increase with detuning, as shown in Fig. 3(a-i), 3(b-i) and 3(c-i). However with further increase in the detuning, the chaos bandwidth of the injected mode will sharply decrease and approach that of the non-injected case (dashed lines in Fig. 3 (a-i)-(c-i)). This dependence arises due to decoupled effects, that is to say the excited high-frequency oscillations decouple from the original chaotic oscillations in the frequency domain. Fig. 3 (a-ii) to (c-ii) shows the overall chaos bandwidth after single -mode injection. We find that in a certain positive frequency detuning range, the bandwidth exhibits almost a linear-increase, no matter which mode is injected. The maximum of bandwidth in these three modes separate injection is 20.5 GHz, 25.3 GHz, and 22.2 GHz. Compared with the no-injection case (BW=7.4 GHz), the bandwidth of chaos increases to threefold after single -mode injection. This result is similar like injection-locked single-mode semiconductor laser with optical feedback, where the bandwidth of single-mode semiconductor laser is expanded roughly three times by strong optical injection compared with the bandwidth without injection [22,23].

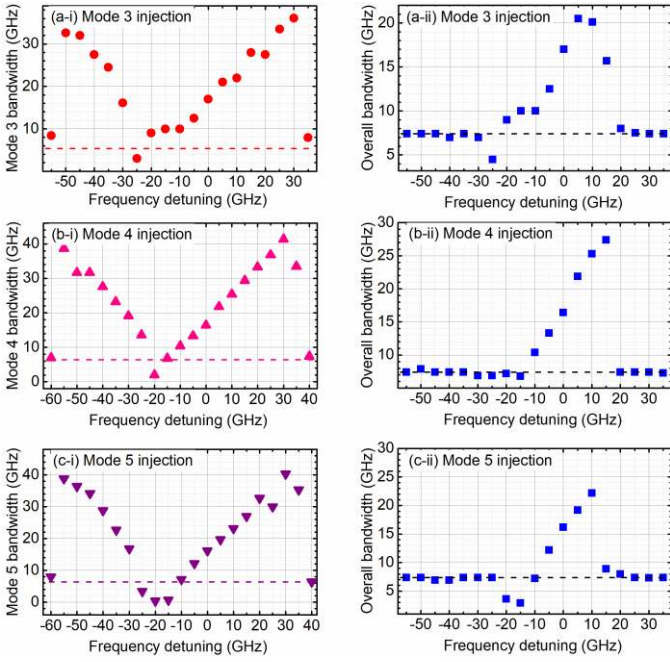


Fig. 3 Bandwidth of the injected mode (left row) and the overall chaos (right row) vs. frequency detuning. (a-i): mode 3 injection with  $k_{inj-M3}=50 \text{ ns}^{-1}$  denotes by red circles; (b-i): mode 4 injection denotes by up-triangles with  $k_{inj-M4}=55 \text{ ns}^{-1}$ ; (c-i): mode 5 injection denotes by down-triangles with  $k_{inj-M5}=55 \text{ ns}^{-1}$ ; (a-ii) - (c-ii): bandwidth of overall chaos corresponding the (a-i) – (c-i) cases. The bandwidth of mode 3, mode 4, mode 5 and overall chaos without injection are 5.4 GHz, 6.4 GHz, 6.4 GHz and 7.4 GHz, which are showing as dashed lines in (a-i)–(c-ii).

Figure 4 gives the rf spectra of the injected chaotic laser when the injected light beam (DFB-LD1) is detuned 15 GHz from mode 3 of the FP-LD. The bandwidth of the injected mode 3 of FP-LD increases to 28 GHz, due to the beating between injection and the original chaotic oscillation. The peak in optical spectra of original chaotic signal is red-shifted by about 10 GHz from each of the free running modes as shown in Fig. 2(a). After injection, the original chaotic signal will undergo a further red-shift induced by the change of carrier density, the beating interaction between injection light and the its neighboring longitudinal mode 3 and extended cavity modes. This results in high-frequency oscillations with broad linewidths around 15 GHz and 30 GHz, as shown in Fig. 4(a). Therefore, the injected mode 3 of FP-LD shows broad chaos bandwidth. For the FP-LD, the cross-correlation between nearest-neighbor modes is negative and is positive otherwise. This causes the low frequency range (0-5 GHz) in the chaos rf spectra for a given injected single-mode to be different from that of the overall chaos. Moreover from the rf spectrum in Fig. 2(b), we can see that the power is mainly concentrated near the relaxation oscillation frequency. These factors lead to low frequency components containing a large part of energy, and 80% energy is around 15 GHz as shown in Fig. 4(b).

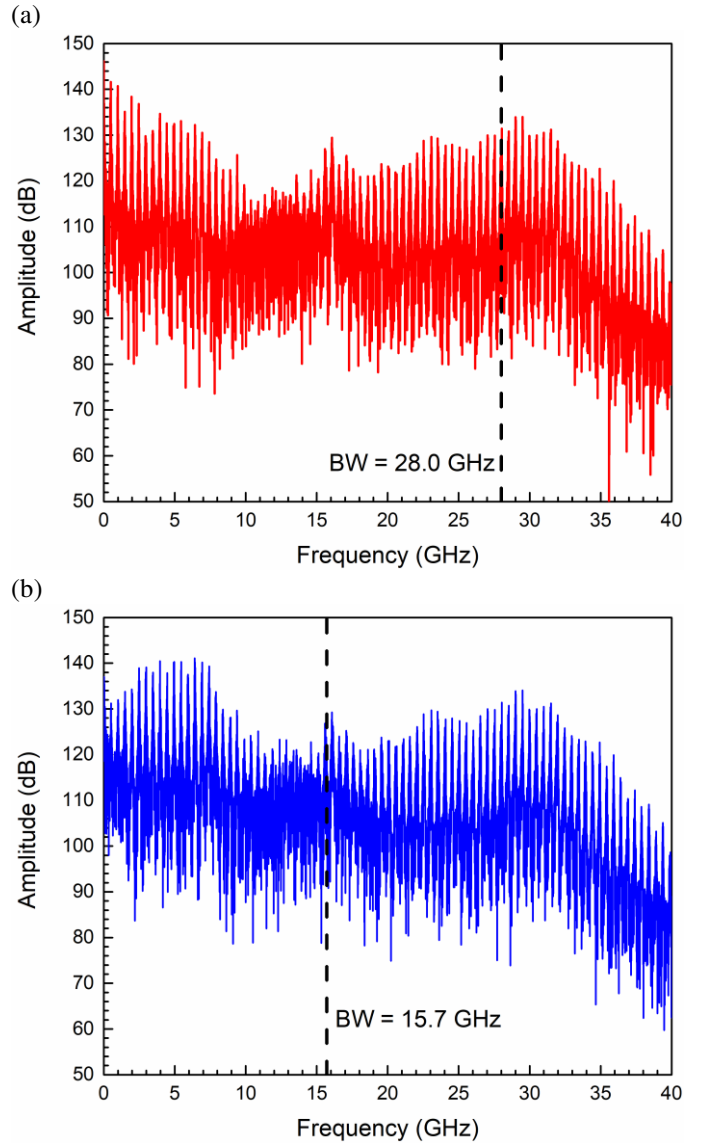


Fig. 4 rf spectra of injected chaotic laser signal with mode 3 injection. Injection amplitude strength is  $50 \text{ ns}^{-1}$ , and detuning between mode 3 of FP-LD and wavelength of DFB-LD1 is 15 GHz. (a) the injected mode 3; (b) the overall chaos of FP-LD.

#### IV. DUAL-MODE INJECTION

In this part we employ dual-mode injection, DFB-LD1's wavelength is close to mode 3 of FP-LD and DFB-LD2's wavelength corresponds to mode 4 or mode 5 of the FP-LD. Here the influence of detuning effects, mode effects, optical injection strength and bias currents on the chaos bandwidth are investigated.

##### A. Detuning Effects

When we fix DFB-LD1 wavelength at 15 GHz detuning from mode 3 of FP-LD, the bandwidth of chaos is 15.7 GHz as the red dashed line shows in Fig. 5. With injection also from DFB-LD2, whose wavelength is around mode 4 of FP-LD, the chaos bandwidth initially increases with increased detuning then decreases under dual-mode injection, as shown in Fig. 5. The increase of bandwidth is caused by beating effects, while the



decrease is due to the decoupling effects discussed previously in relation to single mode injection. We observe that the area of enhancement of bandwidth for the positive detuning is wider than that for negative detuning.

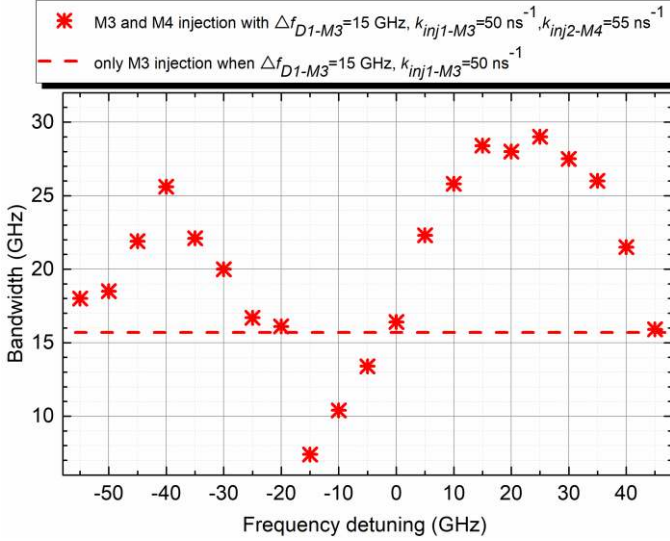


Fig. 5 Bandwidth of chaos vs. frequency detuning between DFB-LD2 and mode 4 of FP-LD.

Figure 6 gives one example of the rf spectra of chaotic laser signal with dual-mode injection, where DFB-LD1 is detuned 15 GHz from mode 3 of the free running FP-LD and DFB-LD2 is detuned 25 GHz from mode 4 of the free running FP-LD. As expected, a higher frequency oscillation around 40 GHz with relative high energy occurs in rf spectra caused by DFB-LD2 injection with a large detuning. It can be observed that after dual-mode injection the bandwidth of chaotic signal further increases to 29 GHz compared with single -mode injection as shown in Fig. 4(b).

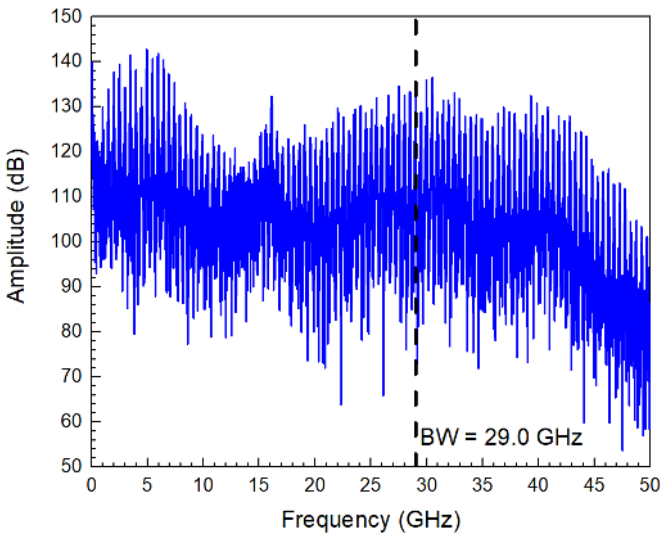


Fig. 6 rf spectra of chaotic laser signal with mode 3 and mode 4 injection. The wavelengths of DFB-LD1 and DFB-LD2 are 15 GHz detuning from mode 3 and mode 4 of FP-LD respectively. The injection amplitude strengths are  $50 \text{ ns}^{-1}$  and  $55 \text{ ns}^{-1}$  separately.

## B. Mode Effects

As shown in Fig. 5, positive frequency detuning is preferred to achieve wideband chaos, we therefore mainly focus on positive detuning cases in the following sections. In section B, some combinations of modes are investigated, such as mode 3 and mode 4 injection, and mode 3 and mode 5 injection. We fix DFB-LD1 as being detuned 15 GHz from mode 3 of FP-LD and change the wavelength of DFB-LD2 so that is close to mode 4 ( $\square$ ) or mode 5 ( $\blacktriangle$ ). As shows in Fig. 7, the bandwidth increases firstly when detuning ranges from 0 GHz to 15 GHz and decreases as detuning further increases. A similar trend is observed when the wavelength of DFB-LD2 is detuned 18 GHz from mode 4 of FP-LD and change the wavelength of DFB-LD1 making it close to mode 3 ( $\bullet$ ). In positive detuning cases, a linear increase of bandwidth is confirmed by experiments [25].

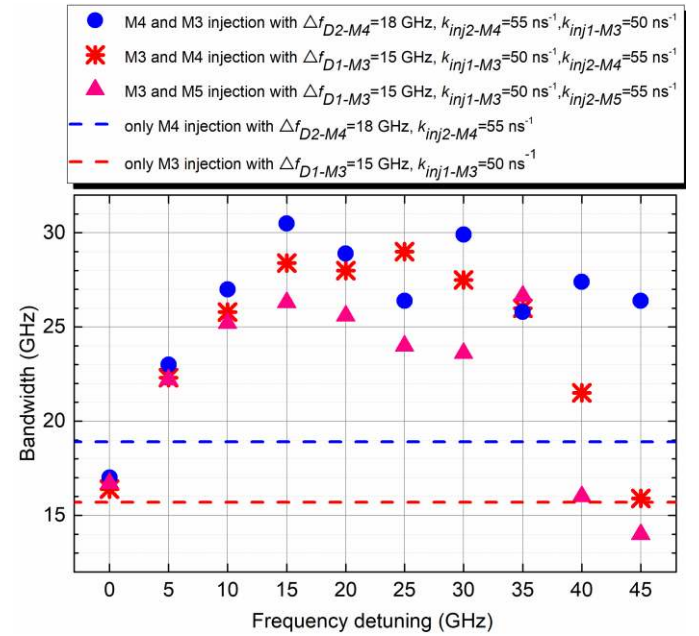


Fig. 7 Bandwidth of chaos vs. frequency detuning.

## C. Injection Strength Effects

In this section we will reveal the impact of the injection strength on the chaos bandwidth and output intensity of overall mode FP-LD. Here both injection strengths from DFB-LD1 and DFB-LD2 are taken to be the same, and their central wavelengths are respectively around mode 3 and mode 4 of FP laser. This arrangement is also used in Section D. Fig. 8 shows that when the injection strength is relatively weak the chaos bandwidth is the same for the case of as no-injection, that is 7.4 GHz. As the injection strength increasing, a relatively sudden increase in bandwidth occurs then the bandwidth increases more slowly and reaches a relatively stable value. We also find that with detuning combinations of DFB-LD1 and DFB-LD2 of 20 GHz and 25 GHz, the chaos bandwidth may exceed 36 GHz when the injection strength is  $70 \text{ ns}^{-1}$ . Compared with the no-injection situation, there is a fourfold increase in the chaos bandwidth. We also observe that by choosing relatively small

detuning such as 10 GHz for DFB-LD1 and 15 GHz for DFB-LD2, the bandwidth maximum-enhancement is similar like that in single -injection cases (Fig. 3 (a-ii)-3(c-ii)) about three times the bandwidth of the original chaos. The underlying physical reason is that each mode of FP laser has a linearly-increasing detuning range as shown in Fig. 3(a-i)-3(c-i) due to beating effects, which leads to the bandwidth of the injected mode increasing with increased detuning. Therefore, a relatively large detuning combination leads to a bandwidth greater than 30 GHz bandwidth. This result is in accordance with our experiments [25].

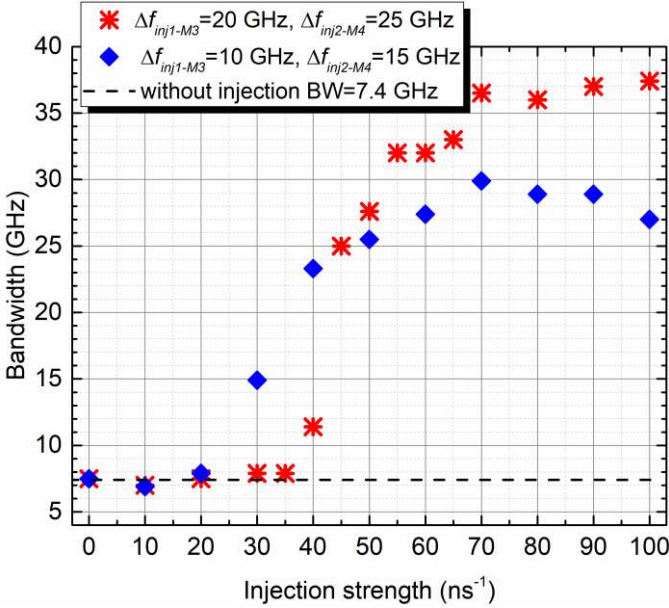


Fig. 8 Bandwidth of chaos vs. injection strength.

Figure 9 shows the normalised output power of the FP-LD without (Fig. 9(a)) and with dual-mode optical injection, for cases of  $k_{inj1-M3} = k_{inj2-M4} = 40 \text{ ns}^{-1}$  (Fig. 9(b)) and  $k_{inj1-M3} = k_{inj2-M4} = 70 \text{ ns}^{-1}$  (Fig. 9(c)), where the frequency detunings are respectively 20 GHz and 25 GHz. It is observed that the average output intensity of the FP-LD (green dashed lines does not significantly change with increasing optical injection strength. When we increase the optical injection strength from 0 to  $100 \text{ ns}^{-1}$ , the average output of FP-LD is in the range 0.66-0.70. Thus for the cases considered here, the influence of the optical injection strength influence on the average output of FP-LD can be ignored.

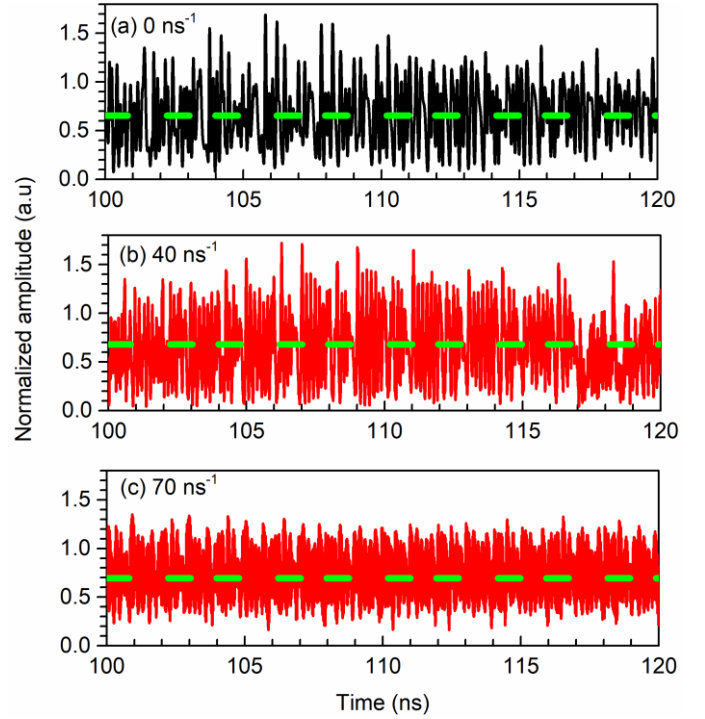


Fig. 9 Intensities of all modes output of FP-LD vs. dual-mode optical injection strength. Detuning between mode 3 of FP-LD and wavelength of DFB-LD1 is 20 GHz, whilst detuning between mode 4 of FP-LD and wavelength of DFB-LD2 is 25 GHz. Dual-mode injection strength is the same which is respectively  $0 \text{ ns}^{-1}$ (a),  $40 \text{ ns}^{-1}$ (b),  $70 \text{ ns}^{-1}$ (c). The dashed line denotes the average output intensity of FP-LD, which is (a) 0.66, (b) 0.68 and (c) 0.70.

#### D. Bias Current Effects

The laser bias current is a key parameter in experimental implementations. A relatively high bias current gives rise a broader bandwidth due to the larger relax oscillation frequency. Here we compare two cases, setting the bias current of the FP-LD in  $1.5I_{th}$  or  $3I_{th}$ , where the frequency detuning between DFB-LDs and FP-LD are respectively  $\Delta f_{inj1-M3} = 20 \text{ GHz}$  and  $\Delta f_{inj2-M4} = 25 \text{ GHz}$ , as shown in Fig. 10(a) and 10(b). As expected, the bandwidth of chaos without injection for a bias current of  $3I_{th}$  is 8.4 GHz, while it is 5.9 GHz when the bias current is  $1.5I_{th}$ . But as the injection strength increases, here the injection strength is greater than  $50 \text{ ns}^{-1}$ , the chaos bandwidth in both these cases exceeds 30 GHz as shown in Fig. 10(a). It is thus apparent that dual-mode injection can realize a chaos bandwidth greater than 30 GHz even at low bias currents. Under this relative low bias current case, the bandwidth of generated chaos increases to six times that of the original chaotic laser. By changing the design of FP-LD, that is increasing the value of cavity decay rate and carrier decay rate, the bandwidth of the original chaos is found to increase due to the larger relaxation oscillation frequency. In these cases it is again found that dual optical injection results in a six fold enhancement of overall chaos bandwidth.

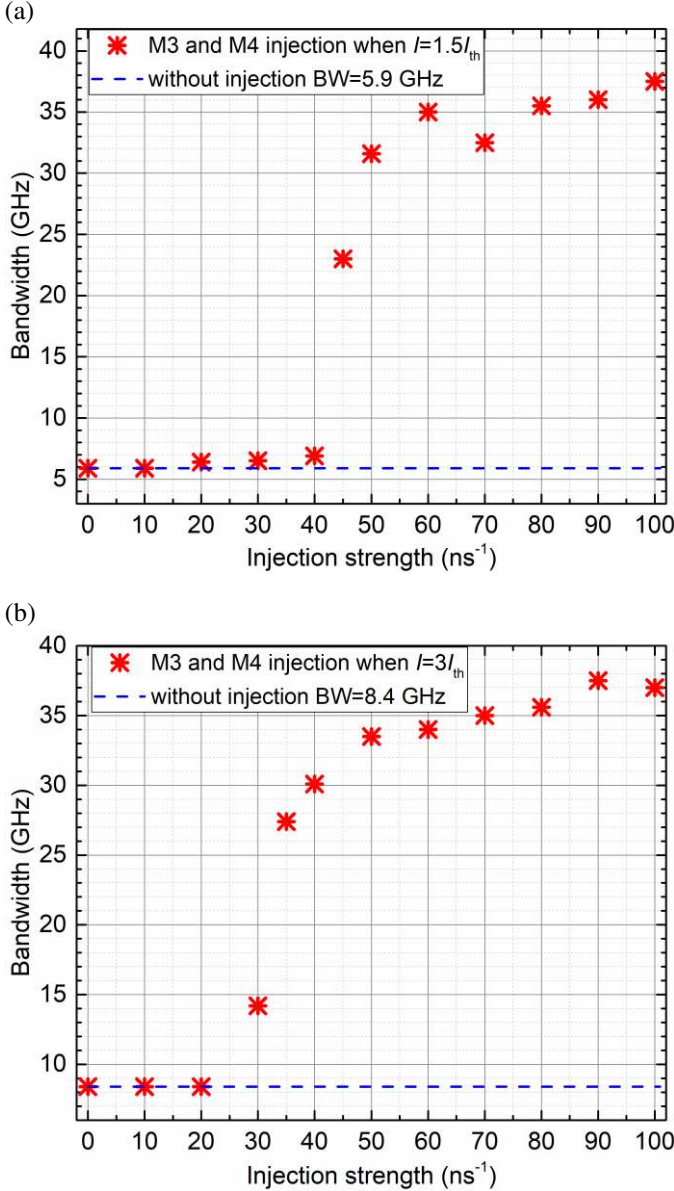


Fig. 10 Bandwidth of chaos vs. injection strength at different bias currents. (a):  $I = 1.5I_{th}$ , (b):  $I = 3I_{th}$ . The bandwidths for  $1.5I_{th}$  and  $3I_{th}$  without injection are 5.9 GHz and 8.4 GHz, respectively. Detuning between mode 3 of FP-LD and wavelength of DFB-LD1 is 20 GHz, whilst detuning between mode 4 of FP-LD and wavelength of DFB-LD2 is 25 GHz.

## V. CONCLUSION

In this paper, we have theoretically investigated chaos bandwidth enhancement in Fabry-Pérot laser diodes using single -mode and dual-mode optical injection from DFB-LDs. Using single mode injection, it has been shown that the chaos bandwidth of each injected mode can be separately excited in both positive and negative detuning range, while within a certain positive detuning range the overall chaos bandwidth can increase to three times of the original chaos. With dual-mode injection, a further enhancement of bandwidth can be obtained – reaching more than 35 GHz. Both detuning and injection

effects are investigated, the tendency of bandwidth enhancement is in accord with previous experiments. Our simulation also found even for low bias current case, bandwidth of chaos can also be significantly enhanced up to 35 GHz which is six times that of the original chaos. Such an enhancement has been found for other sets of device parameters. The results reveal that detuning is a key parameter for the enhancement of chaos bandwidth, which can be further enhanced by increasing optical injection strength and the number of injection modes. In addition, with appropriate choice of the dual-beam injection strength and detuning the bandwidth of chaos is not limited by the magnitude of the bias current, thus providing a wider choice of operating conditions for achieving an enhancement chaos bandwidth.

## REFERENCES

- [1] F. Y. Lin and J. M. Liu, "Chaotic radar using nonlinear laser dynamics," *IEEE J. Quantum Electron.*, vol. 40, no. 6, pp. 815-820, Jun. 2004.
- [2] M. J. Zhang, Y. N. Ji, Y. N. Zhang, Y. Wu, H. Xu and W. P. Xu, "Remote radar based on chaos generation and radio over fiber," *IEEE J. Photon.*, vol. 6, no. 5, pp.7902412, Oct. 2014.
- [3] F. Y. Lin and J. M. Liu, "Chaotic lidar," *IEEE J. Sel. Top. Quantum Electron.*, vol. 10, no. 5, pp. 991-997, Sep. 2004.
- [4] B. J. Wang, H. Xu, Y. Peng, L. Liu and J. X. Li, "Target detection and ranging through lossy media using chaotic radar," *Entropy*, vol. 17, pp. 2082-2093, Apr. 2015
- [5] H. Xu, B. J. Wang, H. Han, L. Liu, J. X. Li, Y. C. Wang and A. B. Wang, "Remote imaging radar with ultra-wideband chaotic signals over fiber links," *Int. J. Bifurcat. chaos*, vol. 25, no.11, pp. 1530029, Apr. 2015.
- [6] Y. C. Wang, B. J. Wang and A. B. Wang, "Chaotic correlation optical time domain reflectometer utilizing laser diode," *IEEE Photon. Technol. Lett.*, vol. 20, no. 19, pp. 1636-1638, Oct. 2008.
- [7] Z. N. Wang, M. Q. Fan, H. Wu, D. V. Churkin, Y. Li, X. Y. Qian and Y. J. Rao, "Long-range and high-precision correlation optical time-domain reflectometry utilizing an all-fiber chaotic source," *Opt. Exp.*, vol. 23, no. 12, pp. 15514-15520, Jun. 2015.
- [8] A. B. Wang, N. Wang, Y. B. Yang, B. J. Wang, M. J. Zhang and Y. C. Wang, "Precise fault location in WDM-PON by utilizing wavelength tunable chaotic laser," *J. Lightw. Technol.*, vol. 30, no.21, pp. 3420-3426, Nov. 2012.
- [9] T. Zhao, A. B. Wang, Y. C. Wang, M. J. Zhang, X. M. Chang, L. J. Xiong, Y. Hao, "Fiber fault location utilizing traffic signal in optical network," *Opt. Exp.*, vol. 21, no. 20, pp. 23978-23984, Oct. 2013.
- [10] T. Zhao, H. Han, J. G. Zhang, X. L. Liu, X. M. Chang, A. B. Wang and Y. C. Wang, "Precise fault location in TDM-PON by utilizing chaotic laser subject to optical feedback," *IEEE Photon. J.*, vol. 7, no.6, p. 6803909, Dec. 2015.
- [11] X. Y. Dong, A. B. Wang, J. G. Zhang, H. Han, T. Zhao, X. L. Liu and Y. C. Wang, "Combined attenuation and high-resolution fault measurements using chaos-OTDR," *IEEE Photon. J.*, vol. 7, no. 6, pp. 6804006, Dec. 2015.
- [12] J. Z. Zhang, M. T. Zhang, M. J. Zhang, Y. Liu, C. K. Feng, Y. H. Wang and Y. C. Wang, "Chaotic Brillouin optical correlation domain analysis," *Opt. Lett.*, 2018, vol. 43, no. 8, pp. 1722-1725, Apr. 2018.
- [13] J. Z. Zhang, C. K. Feng, M. J. Zhang, M. J. Zhang, Y. Liu, Y. C. Wang, Y. H. Wang, "Brillouin optical correlation domain analysis based on chaotic laser with suppressed time delay signature," *Opt. Express*, vol. 26, no. 6, pp. 6962-6972, Mar. 2018.
- [14] A. Uchida, K. Amano, M. Inoue, K. Hirano, S. Naito, H. Somey, I. Oowada, T. Kurashige, M. Shiki and S. Yoshimori, "Fast physical random bit generation with chaotic semiconductor lasers," *Nature Photon.*, vol. 2, no. 12, pp. 728-732, Nov. 2008.
- [15] K. Hirano, T. Yamazaki, S. Morikatsu, H. Okumura, H. Aida, A. Uchida, S. Yoshimori, K. Yoshimura, T. Harayama and P. Davis, "Fast random bit generation with bandwidth-enhanced chaos in semiconductor lasers," *Opt. Exp.*, vol. 18, no. 6, pp. 5512-5524, Mar. 2010.
- [16] A. B. Wang, P. Li, J. G. Zhang, J. Z. Zhang, L. Li and Y. C. Wang, "4.5 Gbps high-speed real-time physical random bit generator," *Opt. Exp.*, vol. 21, no. 17, pp. 20452-20462, Aug. 2013.



- [17] P. Li, Y. Y. Sun, X. L. Liu, X. G. Yi, J. G. Zhang, X. M. Guo, Y. Q. Guo and Y. C. Wang, "Fully photonics-based physical random bit generator," *Opt. Lett.*, vol. 41, no. 14, pp. 3347-3350, Jul. 2016.
- [18] A. Argyris, D. Syvridis, L. Larger, V. Annovazzi-Lodi, P. Colet, I. Fischer, J. García-Ojalvo, C. R. Mirasso, L. Pesquera and K. A. Shore, "Chaos-based communications at high bit rates using commercial fibre-optic links," *Nature*, vol. 438, no. 17, pp. 343-346, Nov. 2005.
- [19] R. Lavrov, M. Jacquot and L. Larger, "Nonlocal nonlinear electro-optic phase dynamics demonstrating 10 Gb/s chaos communications," *IEEE J. Quantum Electron.*, vol. 46, no. 10, pp. 1430-1435, Oct. 2010.
- [20] N. Jiang, W. Pan, L. S. Yan, B. Luo, W. L. Zhang, S. Y. Xiang, L. Yang and D. Zheng, "Chaos synchronization and communication in mutually coupled semiconductor lasers driven by a third laser," *J. Lightw. Technol.*, vol. 28, no. 13, pp. 1978-1986, Jul. 2010.
- [21] L. S. Wang, Y. Q. Guo, Y. Y. Sun, Q. Zhao, D. D. Lan, Y. C. Wang and A. B. Wang, "Synchronization-based key distribution utilizing information reconciliation," *IEEE J. Quantum Electron.*, vol. 5, no. 12, p. 8000208, Dec. 2015.
- [22] Y. Takiguchi, K. Ohyagi and J. Ohtsubo, "Bandwidth-enhanced chaos synchronization in strongly injection-locked semiconductor lasers with optical feedback," *Opt. Lett.*, vol. 28, no. 5, pp. 319-321, Mar. 2003.
- [23] A. B. Wang, Y. C. Wang and H. C. He, "Enhancing the bandwidth of the optical chaotic signal generated by a semiconductor laser with optical feedback," *IEEE Photon. Technol. Lett.*, vol. 20, no. 19, pp. 1633-1635, Oct. 2008.
- [24] X. Q. Qi, L. Xie, Y. P. Liu, "Comparisons of typical nonlinear states in single- and dual-beam optically injected semiconductor lasers," *Opt. Commun.*, vol. 209, pp. 163-169, Dec. 2013.
- [25] M. J. Zhang, T. G. Liu, P. Li, A. B. Wang, J. Z. Zhang and Y. C. Wang, "Generation of broadband chaotic laser using dual-wavelength optically injected Fabry-Pérot laser diode with optical feedback," *IEEE Photon. Technol. Lett.*, vol. 23, no. 24, pp. 1872-1875, Dec. 2011.
- [26] S. Y. Xiang, W. Pen, B. Luo, L. S. Yan, X. H. Zou, N. Q. Li and H. N. Zhu, "Wideband unpredictability-enhanced chaotic semiconductor lasers with dual-chaotic," *IEEE J. Quantum Electron.*, vol. 48, no. 8, pp. 1069-1076, Aug. 2012.
- [27] J. Troger, L. Thévenaz, P.-A. Nicati, and P. A. Robert, "Theory and experiment of a single-mode diode laser subject to external light injection from several lasers," *J. Lightw. Technol.*, vol. 17, no. 4, pp. 629-636, Apr. 1999.
- [28] W. Li, N. H. Zhu, L. X. Wang, J. H. Ke, S. F. Chen, X. Q. Qi, B. H. Zhang, and L. Xie, "Frequency-pushing effect in single-mode diode laser subject to external dual-beam injection," *IEEE J. Quantum Electron.*, vol. 46, no. 5, pp. 796-803, May 2010.
- [29] X.-Q. Qi and J. M. Liu, "Dynamics scenarios of dual-beam optically injected semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 47, no. 6, pp. 762-769, Jun. 2011.
- [30] Y. S. Juan and F. Y. Lin, "Photonic generation of broadly tunable microwave signals utilizing a dual-beam optically injected semiconductor laser," *IEEE Photonic J.*, vol. 3, no. 4, pp. 644-650, Aug. 2011.
- [31] Y. Q. Ding, A. B. Wang, M. J. Zhang, H. C. He, X. C. Li and Y. C. Wang, "Wavelength conversion of chaotic message through gain modulation by injection-locked Fabry-Perot laser diode," *Chin. Opt. Lett.*, vol. 8, pp. 368-371, Apr. 2010.
- [32] J. M. Buldú, J. García-Ojalvo, and M. C. Torrent, "Demultiplexing chaos from multimode semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 41, no. 2, pp. 164-170, Feb. 2005.
- [33] N. Jiang, C. P. Xue, Y. X. Lv and K. Qiu, "Physically enhanced secure wavelength division multiplexing chaos communication using multimode semiconductor lasers," *Nonlinear Dyn.*, vol. 86, no. 3, pp. 1937-1949, Nov. 2016.
- [34] G. Q. Xia, Z. M. Wu, Q. Yang and X. D. Lin, "Modulation response performances of a Fabry-Perot semiconductor laser subjected to light injection from another Fabry-Perot semiconductor laser," *Chinese Sci. Bull.*, vol. 54, pp. 3643-3648, Oct. 2009.
- [35] H. M. Obaid, M. K. Islam and M. O. Ullah, "Simulation experiments to generate broadband chaos using dual-wavelength optically injected Fabry-Perot laser," *J. Mod. Optic.*, vol. 63, no. 15, pp. 1500-1505, Mar. 2016.
- [36] R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties," *IEEE J. Quantum Electron.*, vol. 16, no. 3, pp. 347-355, Mar. 1980.
- [37] F. Y. Lin and J. M. Liu, "Nonlinear dynamical characteristics of an optically injected semiconductor laser subject to optoelectronic feedback," *Opt. Commun.*, vol. 221, no. 1, pp. 173-180, Jun. 2003.

**Hong Han** received the B.S. degree in physics from the University of Jiamusi, Jiamusi, China, and the Ph.D. degree from Harbin Institute of Technology, Harbin, China.

She was a Lecturer at the Taiyuan University of Technology in 2014-2017 and then she became an Associate Professor in 2017. Dr. Han is currently a post-doctoral researcher at Bangor University. Her research work is in dynamic features of chaotic lasers and chaotic security communication. She is a member of OSA.

**Ming Jiang Zhang** received the Ph.D. degree in optics engineering from Tianjin University, Tianjin, China, in 2011. His dissertation was selected to the National Excellent Doctoral Dissertation nomination papers of China. He was a Visiting Scholar with the University of Ottawa during 2015-2016. He is currently a Distinguished Professor of "San Jin Scholar" with Taiyuan University of Technology, Taiyuan, China. He is the Vice Dean of the College of Physics and Optoelectronics. He has co-authored more than 100 journal and conference papers. He holds 17 registered patents. His research interests include nonlinear dynamics of laser diodes, photonic-integrated broadband chaotic signal generator, optical fiber sensing, and microwave photonics.

Prof. Zhang is a member of OSA, IEEE.

**K. Alan Shore** (SM'95) received the degree in mathematics from the University of Oxford, Oxford, U.K., and the Ph.D. degree from University College, Cardiff, Wales, UK.

He was a Lecturer at the University of Liverpool, 1979-1983, and then at the University of Bath where he became a Senior Lecturer in 1986, a Reader in 1990, and a Professor in 1995. He was a Visiting Researcher at the Center for High Technology Materials, University of New Mexico, Albuquerque, USA, in 1987. In 1989, he was a Visiting Researcher at the Huygens Laboratory, Leiden University, Netherlands. During the summers of 1990 and 1991, he was with the Teledanmark Research Laboratory and the MIDIT Center of the Technical University of Denmark, Lyngby. He was a Guest Researcher at the Electrotechnical Laboratory Tsukuba, Japan, in 1991. In 1992, he was a Visiting Professor at the Department of Physics, University de les Illes Balears, Palma-Mallorca, Spain. He was a Visiting Lecturer in the Instituto de Fisica de Cantabria, Santander, Spain, in June 1996 and 1998, and a Visiting Researcher in the Department of Physics, Macquarie University, Sydney, Australia, in 1996, 1998, 2000, 2002, 2005, and 2008. In July/August 2001, he was a Visiting Researcher at the ATR Adaptive Communications Laboratories, Kyoto, Japan. In 1995, he was appointed to the chair of Electronic Engineering at Bangor University where he has been the Head of the School of Informatics and of the College of Physical and Applied Sciences. Between 2001 and 2008, he was the Director of "Industrial and Commercial Optoelectronics," a Welsh Development Agency Centre of Excellence. He was the Chair of the Welsh Optoelectronics Forum from 2006 to 2008 and has chaired the Photonics Academy for Wales, since its establishment in 2005. From 2008 to 2011, he was the Chair of the Quantum Electronics Commission of the International Union of Pure and Applied Physics. In 2015 he coordinated activities in Wales related to the International Year of Light. In

2017 he chaired the Science and Technology Committee of the National Eisteddfod of Wales. His research work has been principally in the area of semiconductor optoelectronic device design and experimental characterization with particular emphasis on nonlinearities in laser diodes and semiconductor optical waveguides. He has authored or co-authored more than 1000 contributions to archival journals, books, and technical conferences. With Prof. D. Kane he co-edited the research monograph *Unlocking Dynamical Diversity*. His current research interests include the dynamics of vertical-cavity semiconductor lasers, applications of nonlinear dynamics in semiconductor lasers, and the design of nano-spin semiconductor lasers.

Prof. Shore cofounded and from 1987 to 2012 acted as the Organizer and Program Committee Chair for the International Conference on Semiconductor and Integrated Optoelectronics, which is held annually in Cardiff, Wales, UK. He has been a Program Member for several OSA conferences and was a Co-organizer of a Rank Prize Symposium on Nonlinear Dynamics in Lasers held at the Lake District, U.K., in August 2002. He chaired the Education and Training in Optics and Photonics conference held at the Technium OptIC, Wales, 2009. He received the Royal Society Travel Grant to visit universities and laboratories in Japan in July 1988. From July to December 2010, he held a Japan Society for the Promotion of Science Invitation Fellowship in the Ultrafast Photonics Group, Graduate School of Materials Science, Nara Institute of Science and Technology, Nara, Japan. He is a Fellow of the Optical Society of America, the Institute of Physics, and the Learned Society of Wales for which he has served as a Council Member (2012–2015 and 2016-2019) and General Secretary 2017-2020.