

Critical dispersion of chirped fiber Bragg grating for eliminating time delay signature of distributed feedback laser chaos

Da-Ming Wang(王大铭), Yi-Hang Lei(雷一航), Peng-Fei Shi(史鹏飞), and Zhuang-Ai Li(李壮爱)
Citation: Chin. Phys. B, 2023, 32 (**9**): 090505. DOI: 10.1088/1674-1056/acddce
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

A novel fractional-order hyperchaotic complex system and its synchronization

Mengxin Jin(金孟鑫), Kehui Sun(孙克辉), and Shaobo He(贺少波)
Chin. Phys. B, 2023, 32 (**6**): 060501. DOI: 10.1088/1674-1056/acc0f6

Unstable periodic orbits analysis in the Qi system

Lian Jia(贾莲), Chengwei Dong(董成伟), Hantao Li(李瀚涛), and Xiaohong Sui(眭晓红)
Chin. Phys. B, 2023, 32 (**4**): 040502. DOI: 10.1088/1674-1056/aca9c3

A color image encryption algorithm based on hyperchaotic map and DNA mutation

Xinyu Gao(高昕瑜), Bo Sun(孙博), Yinghong Cao(曹颖鸿), Santo Banerjee, and Jun Mou(牟俊)
Chin. Phys. B, 2023, 32 (**3**): 030501. DOI: 10.1088/1674-1056/ac8cdf

Lossless embedding: A visually meaningful image encryption algorithm based on hyperchaos and compressive sensing

Xing-Yuan Wang(王兴元), Xiao-Li Wang(王晓丽), Lin Teng(滕琳), Dong-Hua Jiang(蒋东华), and Yongjin Xian(咸永锦)
Chin. Phys. B, 2023, 32 (**2**): 020503. DOI: 10.1088/1674-1056/aca149

Realizing reliable XOR logic operation via logical chaotic resonance in a triple-well potential system

Huamei Yang(杨华美) and Yuangen Yao(姚元根)
Chin. Phys. B, 2023, 32 (**2**): 020501. DOI: 10.1088/1674-1056/ac6945

Critical dispersion of chirped fiber Bragg grating for eliminating time delay signature of distributed feedback laser chaos

Da-Ming Wang(王大铭)[1,†], Yi-Hang Lei(雷一航)[1], Peng-Fei Shi(史鹏飞)[1], and Zhuang-Ai Li(李壮爱)[2]

[1] *School of Information, Shanxi University of Finance and Economics, Shanxi* 030006, *China*
[2] *School of Humanities, Communication University of Shanxi, Jinzhong* 030619, *China*

(Received 8 March 2023; revised manuscript received 13 May 2023; accepted manuscript online 13 June 2023)

Optical chaos has attracted widespread attention owing to its complex dynamic behaviors. However, the time delay signature (TDS) caused by the external cavity mode reduces the complexity of optical chaos. We propose and numerically demonstrate the critical dispersion of chirped fiber Bragg grating (CFBG) for eliminating the TDS of laser chaos in this work. The critical dispersion, as a function of relaxation frequency and bandwidth of the optical spectrum, is found through extensive dynamics simulations. It is shown that the TDS can be eliminated when the dispersion of CFBG is above this critical dispersion. In addition, the influence of dispersive feedback light and output light from a laser is investigated. These results provide important quantitative guidance for designing chaotic semiconductor lasers without TDS.

Keywords: chaos, semiconductor laser, time delay signature, chirped fiber Bragg grating (CFBG)

PACS: 05.45.Pq, 05.45.Gg, 42.55.Px **DOI:** 10.1088/1674-1056/acddce

1. Introduction

Owing to the complex dynamic characteristics, the chaotic laser has great potential applications in secure communication,[1–4] key distribution,[5–10] random number generation,[11–15] and optical neural networks.[16–18] A common approach is to use an external cavity semiconductor laser to generate optical chaos. However, the external cavity mode introduced in the external cavity feedback causes the time delay signature (TDS) in chaotic laser and reduces its complexity.[19]

Many methods have been proposed to solve this problem, including special external cavity feedback,[20,21] and external nonlinear devices.[22–30] In the special external cavity feedback method, an ultrashort external cavity length[20] or two roughly equal cavities are proposed to hide TDS.[21] In the external nonlinear device method, the nonlinear response of a nonlinear device is utilized to reduce the correlation between the output light and the feedback light, such as an additional laser,[22] phased-array feedback,[23] phase-modulated feedback,[24,25] random grating feedback,[26] FBG feedback[27,28] and chirped FBG (CFBG) feedback.[29,30]

In previous study, we have found that dispersion is a meaningful parameter, and a reasonable setting can achieve the complete elimination of TDS.[29] The reason for the elimination of TDS is the nonlinear feedback caused by the dispersion of CFBG. Unlike the fixed external cavity feedback, the dispersive feedback brings an increasing delay time which is related to the resonance frequency. Although the CFBG feedback scheme has proven to be able to eliminate the TDS, the critical dispersion of CFBG is the key to generating a non-periodic chaotic laser in practical application. It should be mentioned that previous work has paid attention to the mechanism of TDS elimination in which dispersive feedback light forms CFBG induced irregular external-cavity mode. By comparison, this work focuses on the critical dispersion range of CFBG which could eliminate the TDS of laser chaos.

In this work, the dispersion of CFBG and the internal parameters of a DFB laser are quantitatively analyzed. In addition, the relationship between these parameters and the critical dispersion is studied. An empirical formula for the critical dispersion of CFBG is obtained by using the modified Lang–Kobayashi model. The TDS can be eliminated in a wide area where the dispersion exceeds the critical dispersion value. Furthermore, these results provide important quantitative guidance for the design of chaotic semiconductor lasers.

2. Theoretical mode

The configuration of dispersion feedback of the DFB laser is illustrated in Fig. 1. A CFBG is used to obtain the dispersion feedback light. The inset shows the group delay spectrum of CFBG and the optical spectrum. Numerical simulations are conducted by using the well-known Lang–Kobayashi equations.[31] By adding the dispersive feedback item, the modified rate equations can be written as follows:[29,30]

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{1+\mathrm{i}\alpha}{2}\left[\frac{g(N-N_0)}{1+\varepsilon|E|^2} - \frac{1}{\tau_\mathrm{p}}\right]E + \frac{\kappa_\mathrm{f}}{\tau_\mathrm{in}}\int_{t-T}^{t} h(t-t')E(t'-\tau)\,\mathrm{d}t', \tag{1}$$

$$\frac{\mathrm{d}N}{\mathrm{d}t} = \frac{I}{qV} - \frac{N}{\tau_\mathrm{N}} - \frac{g(N-N_0)}{1+\varepsilon|E|^2}|E|^2, \tag{2}$$

†Corresponding author. E-mail: wangdaming033@163.com

© 2023 Chinese Physical Society and IOP Publishing Ltd

where E represents the slowly varying amplitude of the electrical field, N being the carrier density, α being the linewidth enhancement factor, g being the differential gain, N_0 being the transparency carrier density, ε being the gain saturation parameter, τ_p being the photon lifetime, τ_{in} being the round-trip time in the laser cavity, κ_f being the amplitude feedback strength, q being the elementary charge, V being the active layer volume, τ_N being the carrier lifetime, and τ being the round-trip time between the laser and the grating.

Table 1. Simulation parameters.[29]

Parameters	Symbol	Value
Transparency carrier density	N_0	1×10^{6} μm^{-3}
Differential gain	g	0.5625×10^{-3} μm^{-3}·ns^{-1}
Gain saturation parameter	ε	1×10^{-5} μm^{3}
Carrier lifetime	τ_N	2.2 ns
Photon lifetime	τ_p	1.17 ps
Round-trip time in laser cavity	τ_{in}	7.3 ps
Linewidth enhancement factor	α	6.0
Active layer volume	V	100 μm^3
Elementary charge	q	1.602×10^{-19} C
Round-trip time in external cavity	τ	5 ns
Feedback strength	k_f	0.1
Bias current	I	$1.5I_{th}$ ($I_{th}=15.35$ mA)
Effective index	n_{eff}	1.46
Average index change	$\langle\delta n\rangle$	5×10^{-4}
Fringe visibility	ρ	1
Segment of grating	M	200
Length of grating	L	10 cm
Speed of light in vacuum	c	3×10^{8} m/s
Integral time	T	20.48 ns

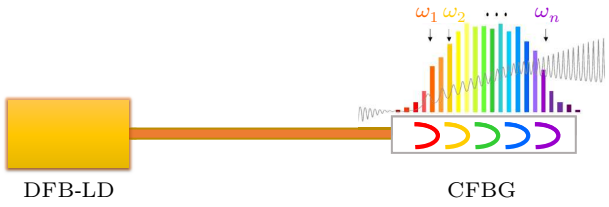


Fig. 1. Schematic diagram of the DFB laser subjected to dispersive feedback from CFBG.

The CFBG feedback is described by the second term on the right-hand side of Eq. (1). The term varies with response function $h(t)$ of the CFBG convoluted with delayed laser field $E(t-\tau)$. T denotes the integral length and its length should be larger than the response time of grating. Since there is no analytical solution for the response function of CFBG, the dispersive feedback term can be computed by taking the inverse Fourier transform of $H(\omega)\cdot\mathrm{FT}\{E(t-\tau)\}$ according to the convolution theorem. Here, FT{ } is the Fourier transform. The reflection spectrum $H(\omega)$ can be calculated by using the piecewise-uniform approach.[29,32] It should be noted that the grating dispersion can be calculated from $100(\mathrm{d}\lambda/\mathrm{d}z)^{-1}$, with $\mathrm{d}\lambda/\mathrm{d}z$ (nm/cm) representing the chirp factor of CFBG. The values of the parameters used in our simulation are summarized in Table 1.

To quantify the TDS, the auto-correlation function (ACF) is expressed as

$$A(\Delta t)=\frac{\langle(I(t+\Delta t)-\langle I(t+\Delta t)\rangle)\cdot(I(t)-\langle I(t)\rangle)\rangle}{\sqrt{\left\langle(I(t+\Delta t)-\langle I(t+\Delta t)\rangle)^2\right\rangle\cdot\left\langle(I(t)-\langle I(t)\rangle)^2\right\rangle}},\tag{3}$$

where $I(t)$ represents the intensity time series, $I(t+\Delta t)$ is the time shift Δt with respect to $I(t)$, and $\langle\cdot\rangle$ denotes average. In the simulation, TDS is evaluated the height of ACF peak around the feedback delay time corresponds to the external cavity.

3. Results and discussion

The CFBG feedback method could eliminate TDS because of the nonlinear feedback from the feedback light. Both the DFB laser and the CFBG are two nonlinear sources in the CFBG feedback system. Therefore, we focus on the relationship between the group delay caused by the dispersion of CFBG and the laser. For the CFBG feedback light, the accumulated group delay of the feedback light can be calculated by using the dispersion and the bandwidth of the optical spectrum. The dispersion is determined by the chirp factor of the CFBG, and the bandwidth is affected by the bias current of the laser, the feedback strength, and the differential gain coefficient.

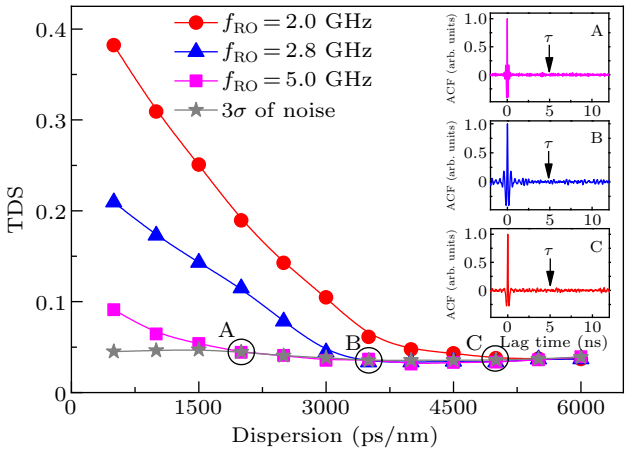


Fig. 2. Results of TDS as a function of CFBG dispersion obtained at f_{RO} values of 2.0 GHz (circle), 2.8 GHz (triangle), and 5 GHz (square). Insets show the ACF curve of chaotic signal corresponding to points A, B, and C. $I=1.5I_{th}$, $\kappa_f=0.1$, and σ denotes the background noise of ACF curve.

Figure 2 shows the curves of TDS as a function of CFBG dispersion at relaxation oscillation frequency of 2.0 GHz (circle), 2.8 GHz (triangle), and 5 GHz (square), respectively. The TDS value is extracted from the ACF traces near the feedback delay ($\tau-0.5$, $\tau+0.5$). The insets show the autocorrelation function (ACF) traces of the chaotic signal corresponding to points A, B, and C. It means that TDS can be eliminated at a feedback delay (5 ns). As the dispersion value increases, TDS gradually reduces until it is submerged in the

background noise floor of the ACF curve. In addition, the results of the three values of relaxation oscillation frequency, i.e., $f_{RO} = 2.0$ GHz, 2.8 GHz and 5.0 GHz, show similar evolution tendencies. Interestingly, the smaller critical dispersion can be obtained at a larger value of f_{RO}.

Figure 3 shows the effects of the f_{RO} and dispersion on the TDS. The colors denote the height of the side peak at the feedback delay time in the ACF curve, and the deeper color represents a lower TDS value. The TDS elimination region is obtained in the dark purple area with obvious boundaries. This boundary can be approximately fitted with a curve which is denoted by a white dashed line. With the increase of f_{RO}, the critical dispersion of eliminating the TDS decreases gradually. When the f_{RO} increases from 2 GHz to 6 GHz, the critical dispersion decreases from 5000 ps/nm to 1100 ps/nm, and the critical dispersion decreases by 78%.

According to the fitting curve, the relationship between critical dispersion (β_c) and f_{RO} can be expressed as

$$\beta_c \times f_{RO} = k(\text{const.}), \tag{4}$$

where k(const.) is a constant and the fitted value is 10. Since the CFBG introduces the nonlinear effect from the optical domain, the relationship between the spectrum of chaotic light and the k(const.) is investigated in the following.

Figure 4 displays the spectra with different f_{RO} values (2 GHz, 3 GHz, 4 GHz, 5 GHz, 5.5 GHz, and 6 GHz) at several critical dispersion points in Fig. 3. The red curves in the optical spectrum of chaotic laser denote their mean fit. It is obvious that the linewidth (−3 dB) of the optical spectrum is roughly 0.1 nm which is exactly equal to the inverse of the k(const.). Therefore, the empirical formula for the critical dispersion can be given as follows:

$$\beta_c = \frac{1}{f_{RO}\Lambda_{-3\text{ dB}}}, \tag{5}$$

where $\Lambda_{-3\text{ dB}}$ denotes the linewidth of the optical spectrum at −3 dB.

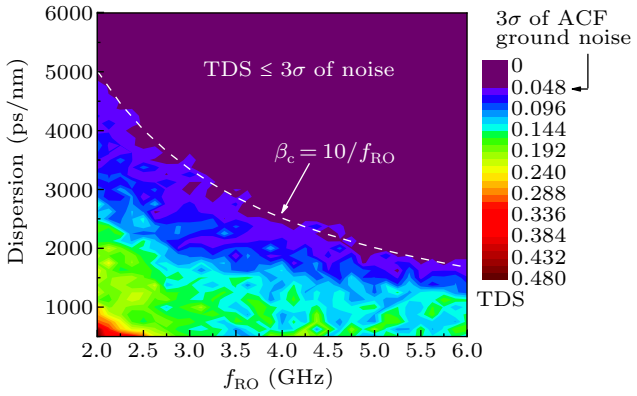


Fig. 3. Effects of parameters (f_{RO} and dispersion) on TDS, with white dash line denoting critical dispersion of CFBG for eliminating TDS, $I = 1.5I_{th}$, and $\kappa_f = 0.1$.

To show the nonlinear effect caused by dispersion more clearly, the correlation between the output light and the dispersive feedback light is shown in Fig. 5. Colors represent the values of the correlation peaks in the cross-correlation curve, and the degree of correlation decreases as the color deepens. Note that the white dash line delineates the critical dispersion range in Fig. 3. The negative dispersive feedback compresses the pulse width in the time domain thus decreasing the value of correlation between the feedback light and the output light. Furthermore, the cross-correlation value gradually decreases as the relaxation oscillation increases. Besides, the correlation value of the feedback and output light ranges from 0.147 to 0.058 along the critical dispersion curve. That means that the critical dispersion value for eliminating TDS is determined by the combined result of both DFB laser and CFBG.

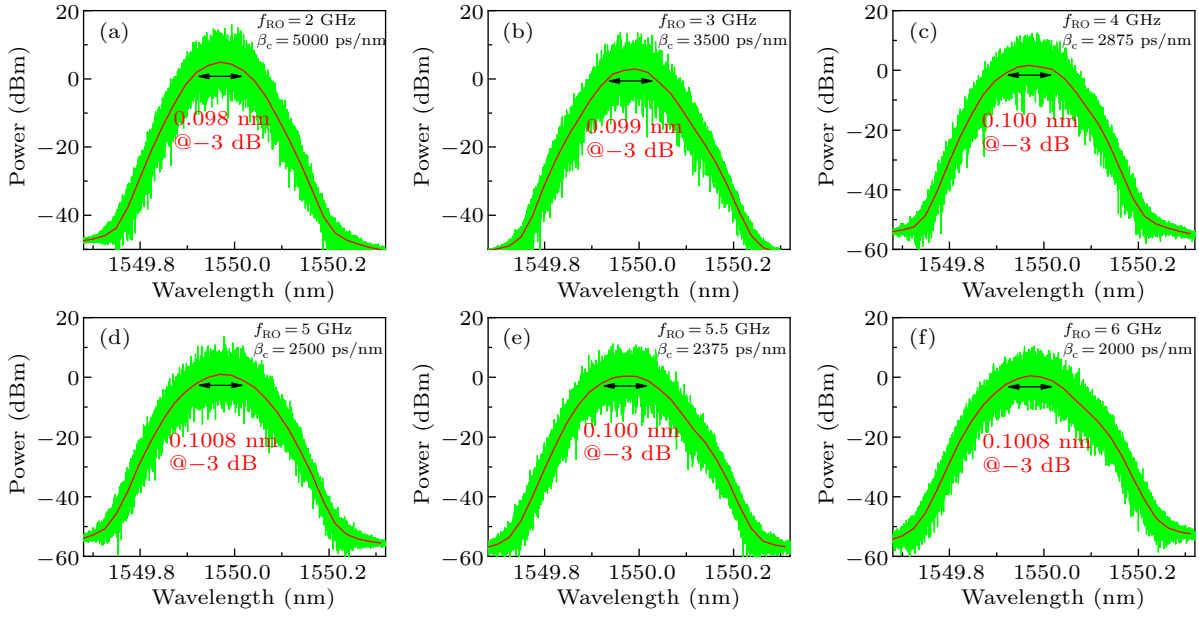


Fig. 4. Numerical results of optical spectra at f_{RO} values of (a) 2 GHz, (b) 3 GHz, (c) 4 GHz, (d) 5 GHz, (e) 5.5 GHz, and (f) 6 GHz.

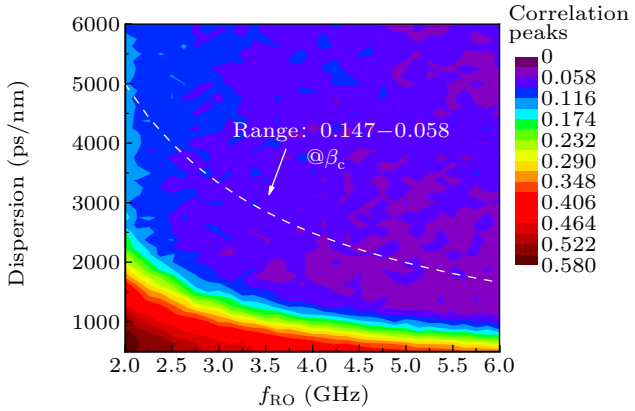


Fig. 5. Effects of parameters (f_{RO}, dispersion) on cross-correlation coefficient of the output light and dispersive feedback light from CFBG. $I = 1.5I_{th}$ and $\kappa_f = 0.1$.

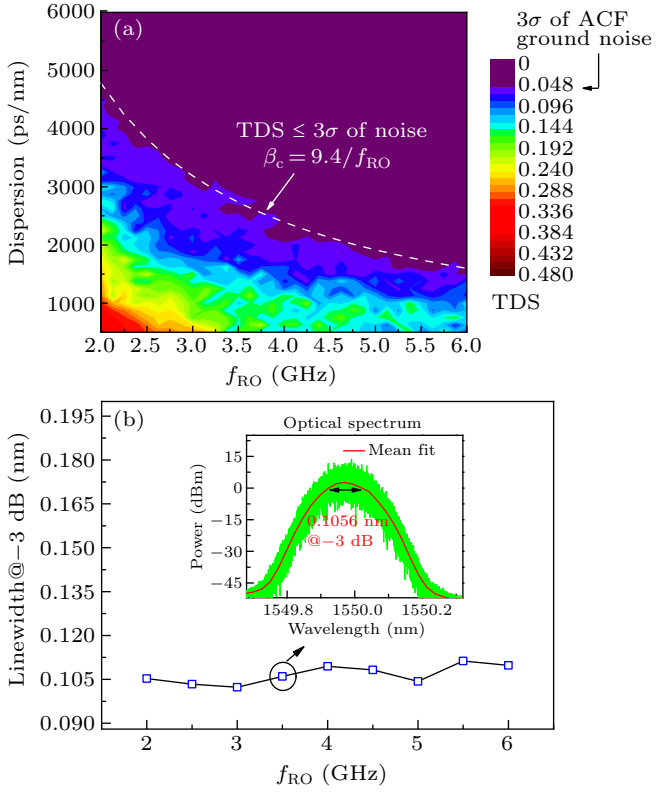


Fig. 6. (a) Effects of parameters (f_{RO}, dispersion) on TDS and (b) effects of f_{RO} on line width of optical spectrum, with dashed line denoting critical dispersion of CFBG for eliminating TDS and insets showing optical spectrum of output light at $I = 1.5I_{th}$ and $\kappa_f = 0.12$.

Furthermore, the results of β_c with feedback strength of 0.12 are exhibited in Fig. 6, including the effect of f_{RO} and dispersion on TDS (Fig. 6(a)) and the effect of f_{RO} on line width of the optical spectrum (Fig. 6(b)). The inset shows the optical spectrum at f_{RO} of 3.5 GHz. It is obvious that the boundary of critical dispersion can be approximately fitted by the dash line ($\beta_c = 9.4/f_{RO}$), where the k(const.) is equal to the inverse of the linewidth. Unlike Fig. 3, the dash line shifts downward and there is a significant decrease with k(const.). The reason is that the optical spectrum has broadened as k_f increases from 0.1 to 0.12. The increase of group delay caused by CFBG and optical spectrum will reduce the correlation between the feedback light and the output light. As a result, the system requires a lower dispersion to eliminate TDS and k(const.) will decrease significantly.

Furthermore, the above formula is verified by changing the bias current of the DFB laser, and the results are shown in Fig. 7. Figure 7(a) shows the effect of f_{RO} and dispersion on TDS. Figure 7(b) displays the effect of f_{RO} on the linewidth (−3 dB) of chaotic light. The insets show two optical spectra under the f_{RO} of 2.5 GHz and 5.5 GHz, respectively. When the f_{RO} value is over 3.5 GHz, the critical dispersion can be approximately fitted as the white dashed line ($\beta_c = 6.9/f_{RO}$) which matches well with the inverse of the linewidth. For the f_{RO} value below 3.5 GHz, the linewidth gradually increases with f_{RO} increasing. The critical dispersion can be correspondingly fitted with the curve related to the empirical formula (5) which is shown by the yellow dotted line in Fig. 7(a). As a result, the empirical formula of critical dispersion is proved. In addition, the bandwidth of spectrum in Fig. 7(b) is stable at about 0.144 nm when the f_{RO} over 3.5 GHz which means that the group delay induced by the CFBG will be stable. Therefore, β_c follows different formulas before and after f_{RO} of 3.5 GHz.

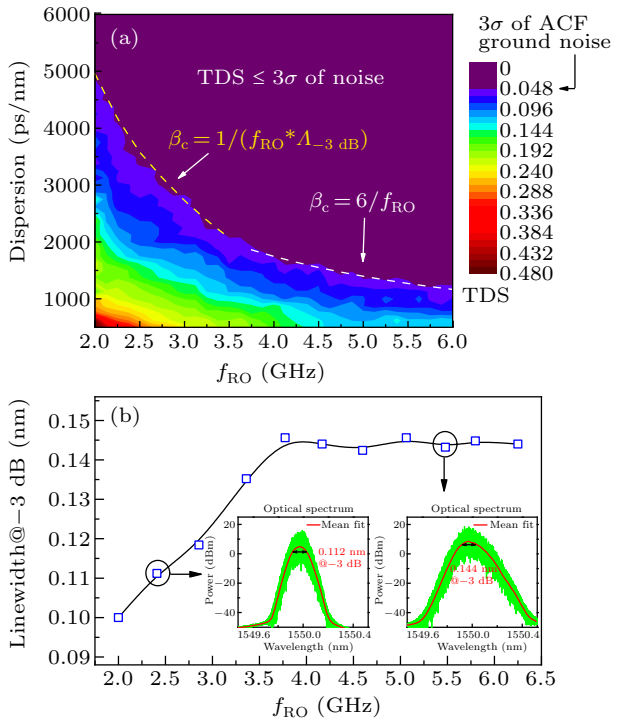


Fig. 7. (a) Effects of parameters (f_{RO}, dispersion) on TDS and (b) effects of f_{RO} on line width of optical spectrum, with dashed line denoting critical dispersion of CFBG for eliminating TDS, and insets showing optical spectrum of output light, at $\kappa_f = 0.1$, and $g = 0.5625 \times 10^{-3}$ μm^3·ns^{-1}.

It is worth noticing that the f_{RO} of a solitary laser (without external feedback) can be obtained according to Ref. [33]. Therefore, f_{RO} is adjusted in the simulation with bias current and differential gain. Figure 8 shows the effect of bias current and differential gain on f_{RO}. The bias current varies from $1.5I_{th}$ to $6I_{th}$, and the differential gain varies from 0.0005 to

0.0045. In addition, it is considered that the feedback light slightly increases the relaxation oscillation frequency of the laser. In order to obtain a more accurate f_{RO}, the f_{RO} in the simulation is obtained from τ_{RO} in the ACF curve ($f_{RO} = 1/\tau_{RO}$) as shown in the inset of Fig. 8.

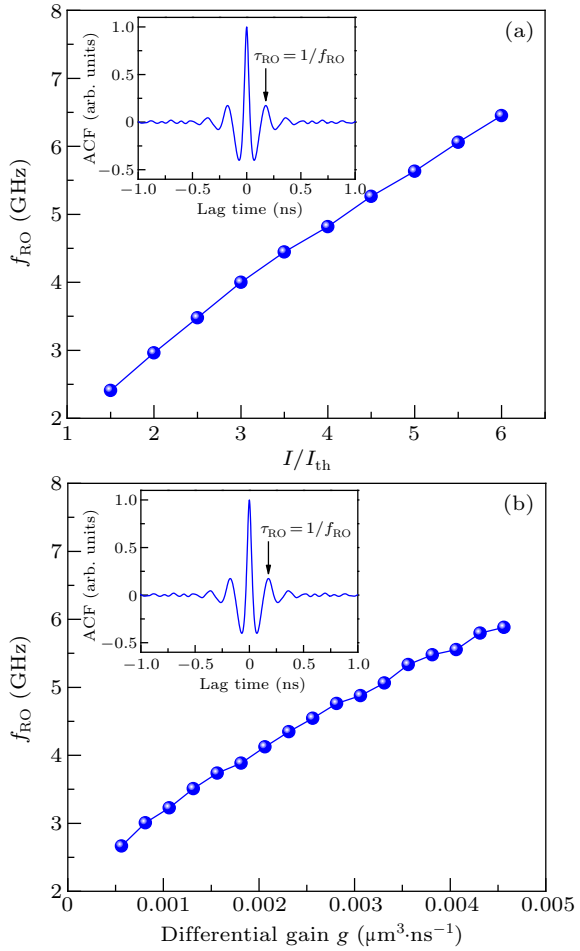


Fig. 8. Effect of (a) bias current and (b) differential gain on f_{RO}, with each of insets showing ACF curve of the chaotic laser output.

4. Conclusion

We conduct extensive simulations to investigate the TDS of a DFB laser with CFBG dispersive feedback, from which a critical dispersion for eliminating TDS can be determined. The nonlinearity in this system is obtained by the laser and the CFBG. For the dispersive feedback light, the external cavity mode will be destroyed while the value of group delay caused by dispersion from CFBG is greater than that of τ_{RO}. At the same time, the output light shows that the TDS disappears. The results show that there is a clear demarcation line in the range where the TDS is eliminated and an empirical formula is obtained. Furthermore, through the analysis of the correlation between the feedback light and the output light, it is found that the elimination of TDS is the result of the joint action of both CFBG and DFB. This study provides a parameter setting basis for a semiconductor laser subjected to CFBG feedback to generate a TDS-free chaotic laser.

Acknowledgments

Project supported by the National Natural Science Foundation of China (Grant No. 62105190), the Natural Science Foundation of Shanxi Province of China (Grant No. 20210302124268), the Scientific and Technological Innovation Programs of Higher Education Institutions of Shanxi Province of China (Grant No. 2021L285), and the Youth Research Foundation Project of Shanxi University of Finance and Economics (Grant No. QN-202015).

References

[1] Argyris A, Syvridis D, Larger L, Annovazzi-Lodi V, Colet P, Fischer I, García-Ojalvo J, Mirasso C R, Pesquera L and Shore K A 2005 *Nature* **438** 343
[2] Lavrov R, Jacquot M and Larger L 2010 *IEEE J. Quantum Electron.* **46** 1430
[3] Xiang S, Yang M and Wang J 2022 *Opt. Lett.* **47** 2818
[4] Gao Z, Liao L, Su B, Wu Q, Gao X, Fu S, Li Z, Wang Y and Qin Y 2022 *Opt. Lett.* **47** 5232
[5] Kanter I, Butkovski M, Peleg Y, Zigzag M, Aviad Y, Reidler I, Rosenbluh M and Kinzel W 2010 *Opt. Express* **18** 18292
[6] Yoshimura K, Muramatsu J, Davis P, Harayama T, Okumura H, Morikatsu S, Aida H and Uchida A 2012 *Phys. Rev. Lett.* **108** 70602
[7] Böhm F, Sahakian S, Dooms A, Verschaffelt G and Van der Sande G 2020 *Phys. Rev. Appl.* **13** 064014
[8] Gao H, Wang A, Wang L, Jia Z, Guo Y, Gao Z, Yan L, Qin Y and Wang Y 2021 *Light Sci. Appl.* **10** 172
[9] Huang Y, Zhou P and Li N 2021 *Opt. Express* **29** 19675
[10] Gao Z, Ma Z, Wu S, Gao H, Wang A, Fu S, Li Z, Qin Y and Wang Y 2022 *Opt. Express* **30** 23953
[11] Uchida A, Amano K, Inoue M, Hirano K, Naito S, Someya H, Oowada I, Kurashige T, Shiki M, Yoshimori S, Yoshimura K, and Davis P 2008 *Nat. Photonics* **2** 728
[12] Kanter I, Aviad Y, Reidler I, Cohen E and Rosenbluh M 2010 *Nat. Photonics* **4** 58
[13] Pu L, Ya G, Guo Y, Fan Y, Guo X, Liu X, Li K, Shore K A, Wang Y and Wang A 2018 *J. Light. Technol.* **36** 2531
[14] Guo Y, Cai Q, Li P, Zhang R, Xu B, Shore K A and Wang Y 2022 *Adv. Photonics* **4** 035001
[15] Huang C, Gao X, Wu S, Gu W, Su B, Wang Y, Qin Y and Gao Z 2022 *Photonics* **9** 952
[16] Ke J X, Yi L and Hu W 2019 *IEEE Photon. Tech. Lett.* **31** 1104
[17] Guo X, Xiang S, Qu Y, Han Y, Wen A and Hao Y 2021 *J. Light. Technol.* **39** 129
[18] Cai Q, Guo Y, Li P, Bogris A, Shore K A, Zhang Y and Wang Y 2021 *Photonics Res.* **9** B1
[19] Rontani D, Locquet A, Sciamanna M, Citrin D S and Ortin S 2009 *IEEE J. Quantum Electron.* **45** 879
[20] Rontani D, Locquet A, Sciamanna M and Citrin D S 2007 *Opt. Lett.* **32** 2960
[21] Wu J, Xia G and Wu Z 2009 *Opt. Express* **17** 20124
[22] Wu J, Wu Z, Xia G and Feng G 2012 *Opt. Express* **20** 1741
[23] Zhou P, Fang Q and Li N 2020 *Opt. Lett.* **45** 399
[24] Jiang N, Zhao A, Liu S, Xue C, Wang B and Qiu K 2018 *Opt. Lett.* **43** 5359
[25] Xiang S, Pan W, Zhang L, Wen A, Shang L, Zhang H and Lin L 2014 *Opt. Commun.* **324** 38
[26] Xu Y, Zhang M, Zhang L, Lu P, Mihailov S and Bao X 2017 *Opt. Lett.* **42** 4107
[27] Li S, Liu Q and Chan S 2012 *IEEE Photon. J.* **4** 1930
[28] Li S and Chan S 2015 *IEEE J. Sel. Top. Quantum Electron.* **21** 541
[29] Wang D, Wang L, Zhao T, Gao H, Wang Y, Chen X and Wang A 2017 *Opt. Express* **25** 10911
[30] Wang D, Wang L, Li P, Zhao T, Jia Z, Gao Z, Guo Y, Wang Y and Wang A 2019 *Photonics* **6** 59
[31] Lang R and Kobayashi K 1980 *IEEE J. Quantum Electron.* **16** 347
[32] Erdogan T 1997 *J. Light. Technol.* **15** 1277
[33] Uchida A 2012 *Optical Communication with Chaotic Lasers: Applications of Nonlinear Dynamics and Synchronization* (Hoboken: Wiley-VCH) pp. 165–166