Experimental investigation on the time-delay signature of chaotic output from a 1550 nm VCSEL subject to FBG feedback

Zhu-Qiang Zhong,1 Zheng-Mao Wu,1,2 and Guang-Qiong Xia1,*

1School of Physical Science and Technology, Southwest University, Chongqing 400715, China
2e-mail: zmwu@swu.edu.cn
*Corresponding author: gqxia@swu.edu.cn

Received October 11, 2016; revised November 15, 2016; accepted November 16, 2016; posted November 18, 2016 (Doc. ID 278477); published December 12, 2016

The time-delay signature (TDS) of chaos output in a 1550 nm vertical-cavity surface-emitting laser (VCSEL) subject to fiber Bragg grating (FBG) feedback is investigated experimentally. Autocorrelation function (ACF) and mutual information (MI) are used for quantitatively identifying the TDS of chaos. For various bias currents, the TDS evolution with the feedback strength is different, as the FBG provides wavelength-selective feedback. Furthermore, based on the TDS map of the FBG feedback VCSEL (FBGF-VCSEL) in the parameter space of feedback strength and bias current, the optimal TDS suppression regions, where the dominant polarization mode of FBGF-VCSEL locates at the edge of the main lobe of FBG reflection spectrum, have been determined. Finally, for comparative purpose, the TDS of chaos in mirror feedback VCSEL (MF-VCSEL) also has been presented, and the results show that an FBGF-VCSEL possesses better TDS suppression performance than an MF-VCSEL. © 2016 Chinese Laser Press

OCIS codes: (140.5960) Semiconductor lasers; (060.3735) Fiber Bragg gratings; (190.3100) Instabilities and chaos

https://doi.org/10.1364/PRJ.5.000006

1. INTRODUCTION

Vertical-cavity surface-emitting lasers (VCSELS) have been widely adopted in various applications such as optical communication, optical storage, parallel optical links, and so on [1–4]. Compared with edge-emitting semiconductor lasers (EELs), VCSELS have many beneficial features such as low power consumption, low threshold current, low cost, on-wafer testing capability, high bandwidth modulation, and easy large-scale integration into 2D arrays, etc. [5,6]. VCSELS subject to suitable optical feedback can generate high Kaplan–Yorke dimension optical chaotic output and then apply to optical-chaos-based communication [1,2,7]. However, the chaotic output from external cavity feedback VCSELS (ECF-VCSELS) usually retains a time-delay signature (TDS) originated from the optical round trip between the VCSEL and the external feedback mirror [8–14], which may provide some possibilities to reconstruct the system by adopting time-series analysis techniques for delayed systems [15–17] and then threaten the system security. As a result, the TDS suppression has been a research hot spot in the field related to chaos generation and applications based on delayed VCSELS in recent years.

So far, many schemes have been proposed for suppressing the TDS of chaos in VCSELS. Xiang et al. numerically investigated the TDS of chaos in VCSELS with single variable-polarization optical feedback (VPOF) [8]. Priyadarshi et al. experimentally demonstrated the TDS concealment in VCSELS subject to VPOF [9]. By introducing another feedback cavity, Lin and co-workers experimentally verified that the TDS in a single transverse and multi-transverse mode VCSEL with double-cavity polarization-rotated feedback can be effectively suppressed [10,11]. Elsonbaty et al. theoretically investigated the TDS of chaos in a hybrid optical and electro-optic feedback VCSEL and successfully achieved TDS of intensity and phase simultaneously suppressed chaotic carriers [12]. Liu et al. proposed a three cascade-coupled configuration of VCSELS and numerically investigated the TDS and chaotic bandwidth of the output from the VCSELS [13]. Hong et al. experimentally verified the performance of the three-cascaded VCSELS in suppressing the TDS of chaos as well as the effect of injecting chaotic bandwidth on the TDS suppression [14]. It should be noted that, for the above-mentioned schemes, external optical feedback is provided by mirrors. Recently, Li et al. proposed and experimentally demonstrated that, by using a fiber Bragg grating (FBG) as a reflector, the TDS of chaos output from an EEL can be suppressed [18,19]. Different from conventional reflected mirrors, an FBG can provide distributed feedback along its length, and the group velocity dispersion of FBG can weaken and suppress the TDS. We extended the FBG feedback to VCSELS and theoretically studied the TDS of chaos in VCSELS subject to variable-polarization FBG feedback [20] as well as the polarization-resolved TDS of chaos in an FBG feedback VCSEL (FBGF-VCSEL) [21]. Even so, no experimental investigation on the TDS of chaotic output from an FBGF-VCSEL has been carried on.

In this work, the TDS of chaotic output from a 1550 nm VCSEL subject to FBG feedback is experimentally investigated. By recording the time series, power spectrum, and optical spectrum of the FBGF-VCSEL output, the dynamical route to chaos of the system is examined. Moreover, with the help of an autocorrelation function (ACF) and mutual
information (MI), the influence of feedback strength and bias current on the TDS is quantitatively analyzed. Finally, we compare the TDS suppression performance between the mirror feedback VCSEL (MF-VCSEL) and the FBGF-VCSEL and determine the optimal TDS suppressed regions by mapping the TDS in the parameter space of feedback strength and bias current.

2. EXPERIMENTAL SETUP

A diagram of the experimental setup is illustrated in Fig. 1. A commercially available 1550 nm VCSEL (Raycan) is adopted in this experiment. The laser is driven and temperature-controlled by an ultra-low-noise current source (ILX-Lightwave, LDC-3724C). The emission of the VCSEL is divided into two parts after passing through a 50/50 fiber coupler (FC1). One part is first amplified by an erbium-doped fiber amplifier (EDFA), reflected by an FBG (Alxenses, Bragg wavelength 1550.62 nm, 3 dB bandwidth 0.42 nm) and then fed back to the VCSEL via an optical circulator (OC), a variable attenuator (VA), and a polarization controller (PC). The other part is sent to be detected after passing through an optical isolator (OI) (isolation >55 dB). An optical spectrum analyzer (OSA, Ando AQ6317C) is employed to observe the optical spectrum distribution. The time series and electrical spectrum of the output of VCSEL can be, respectively, recorded by a digital oscilloscope (OSC, Agilent DSO-X 91604A, 16 GHz bandwidth) and an electrical spectrum analyzer (ESA, Agilent E4407B, 26.5 GHz bandwidth) after being converted to an electric signal by a fast photodetector (PD, u2t, XPDV2150R, 45 GHz bandwidth). The feedback strength can be adjusted by a VA and monitored by a power meter (PM). During the total experimental process, the temperature of the VCSEL is stabilized at 12.20°C, and the feedback time is approximately 244 ns, which is estimated by extracting the frequency interval between two closed external-cavity modes from the power spectrum when the laser operates at a quasi-periodic state [22].

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 shows the measured light-current characteristic of the solitary 1550 nm VCSEL and the optical spectrum when the VCSEL operates at 3.5 mA, where the polarization mode of VCSEL with a shorter wavelength is defined as x polarization (XP) mode. As shown in this diagram, the threshold current of the VCSEL is approximately $I_{th} = 1.7$ mA. In Fig. 2(b), the spacing between two polarization modes of the VCSEL is about 0.28 nm. According to our previous work [23], after introducing an FBG to provide wavelength-selective feedback, multiple dominant polarization mode switching will occur when the feedback strength or the bias current varies. Moreover, under some operation parameters, the TDS of the suppressed polarization mode cannot be extracted because its output power is too weak. Therefore, in this experiment, we focus on the TDS of the total output intensity of the VCSEL.

Before the exploration of TDS of the FBGF-VCSEL, the dynamical route to chaos of the FBGF-VCSEL should be preliminarily investigated. Figure 3 displays the time series, power spectra, and optical spectra of the FBGF-VCSEL under different feedback strength $\xi_f$, and the bias current is set at 4.0 mA. For $\xi_f = 0$ (as shown in row 1), namely, the VCSEL operates at free-running, the time series is nearly a constant level with small ripples, the power spectrum is near to the noise floor, and then the dynamical state can be determined as a stable state. When $\xi_f$ is increased to 0.01 (as shown in row 2), incommensurate frequency peaks emerge around the fundamental frequency and its harmonic frequencies in the power spectrum, and the optical spectrum is broadened compared with that at free-running [Fig. 3(c1)]. As a result, the dynamical state can be assessed to be a quasi-periodic state. Further increasing $\xi_f$ to 0.1, the time series behaves dramatically fluctuating, the optical spectrum is further broadened, and the power spectrum becomes continuous and smooth, which indicates that the dynamical state is in chaos. From the above experimental observations, we can find a quasi-periodic route to chaos with the increase of feedback

![Fig. 1. Experimental setup. Solid line: optical path; dashed line: electronic path.](image-url)
strength, which is in agreement with our previous numerical simulation results [21].

Next, we will focus on the influence of feedback strength \( \xi_f \) on the TDS when the FBGF-VCSEL operates at a chaos state. Here, in order to quantitatively evaluate the TDS, the ACF and the MI are introduced. The former has been mostly adopted to analyze TDS for its simplicity and fast calculation [8–11], and the latter, which is based on the probability analysis, is also widely used for TDS identification [12,19]. Figure 4 shows the time series, power spectrum, ACF, and MI for the chaotic output of the FBGF-VCSEL under different feedback strengths of \( \xi_f = 0.06 \) (row 1), 0.22 (row 2) and 0.50 (row 3). For \( \xi_f = 0.06 \) (row 1), the time series behaves noise-like [Fig. 4(a1)], and it seems difficult to recognize TDS directly from the time domain. However, in the frequency domain, the power spectrum has an enhancement at \(-2\) GHz [Fig. 4(b1)], which is close to the relaxation resonance frequency of the VCSEL when \( I = 4.0 \) mA. If one zooms the frequency span to 20 MHz [the inset of Fig. 4(b1)], some uniform spacing frequency peaks can be observed, and the frequency interval is about 4.10 MHz, which approximately equals to the reciprocal of feedback time. Therefore, the TDS can be roughly identified by the power spectrum. Furthermore, the ACF and MI are calculated with the length of the time series 25 \( \mu \)s, respectively. As seen in Figs. 4(c1) and 4(d1), there exist pronounced peaks labeled by the arrows when the lag time is close to 244 ns and the TDS is relatively obvious. For \( \xi_f = 0.22 \) (row 2), the chaotic time series is still intricate [Fig. 4(a2)], while the power spectrum is broadened in some degree compared with Fig. 4(b1); in the zoomed span, there are no significant spacing frequency peaks, which reveals that the TDS is less pronounced. Further examining the ACF and MI, as shown in Figs. 4(c2) and 4(d2), it can be seen that the TDS is basically invisible and successfully suppressed. As for \( \xi_f = 0.50 \), the time series of the laser output shows chaotic oscillation without obviously recognizable time-delay information; however, from the inset of Fig. 4(b3) some repeating features corresponding to the reciprocal of feedback time emerge. Moreover, when the lag time is close to 244 ns, the peak values of the ACF and MI increase compared with those for \( \xi_f = 0.22 \). These evidences demonstrate that under the case of \( \xi_f = 0.50 \), the TDS has not been suppressed very well. From above discussion, it can be anticipated that the feedback strength \( \xi_f \) plays an important role for TDS suppression in an FBGF-VCSEL, and suitable \( \xi_f \) can effectively conceal the TDS of chaos, which has also been proven in EELs with FBG feedback [18,19].

As FBGs possess the unique characteristic of wavelength-selective reflection together with the emitting wavelength of VCSEL will redshift with the increase of bias current, it can be anticipated that the TDS evolution with the feedback strength under different bias currents will be more complex and interesting. In the following, we will pay attention to this issue. Here, we define the TDS \( \sigma \) as the maximum value of the ACF in the lag time region of \([240 \text{ ns}, 248 \text{ ns}]\). Figure 5 presents the optical spectra of the free-running VCSEL and FBG reflection spectrum, and the corresponding TDS evolution as a function of feedback strength under different bias currents of \( I = 3.0 \) mA (row 1), \( I = 3.5 \) mA (row 2), and \( I = 4.0 \) mA (row 3). Besides, in order to compare the TDS suppression performance between a mirror and an FBG, the experimental comparison results with a mirror feedback also have been provided. For \( I = 3.0 \) mA (row 1), the YP mode locates at the left sideband of FBG reflection spectrum and then gets less reflectivity compared with the XP mode because the XP mode enters the main lobe of the FBG reflection spectrum. As a result, the XP mode will play a dominant role with increased \( \xi_f \), which may induce polarization mode switching. With the increase of feedback strength \( \xi_f \), the TDS of the FBGF-VCSEL chaos output first rapidly decreases to a minimum of about 0.08 at \( \xi_f = 0.06 \) and then gradually increases to a relatively stable level, which is in agreement with our theoretical prediction [21]. The situations for \( I = 4.0 \) mA (row 3) are similar with those for \( I = 3.0 \) mA except that the YP mode always plays a dominant role, and no polarization mode switching happens due to the XP mode located at the main lobe of the FBG reflection spectrum, while the XP mode is at the right sideband of the FBG reflection spectrum. As for \( I = 3.5 \) mA (row 2), the situation may be complicated because both the XP and YP modes enter the main lobe of FBG reflection spectrum, and the two-mode coexistence may appear [23], and then the TDS evolution presents a gradually declining trend within the experimental range of feedback strength. In general, compared with MF-VCSEL, the TDS of
the chaotic output from FBGF-VCSEL has a lower level than that of MF-VCSEL, which reveals that FBGF-VCSEL may possess better TDS suppression performance than an MF-VCSEL.

The above results show that the feedback strength $\xi_f$ and the bias current $I$ are two key parameters to seriously affect the TDS suppression of FBGF-VCSEL. Finally, the TDS of chaos will be further investigated when $\xi_f$ and $I$ simultaneously vary. Figure 6 presents the mappings of the TDS $\sigma$ of both FBGF-VCSEL and MF-VCSEL in the parameter space of $\xi_f$ and $I$, where different colors correspond to different values of $\sigma$. The dashed line in Fig. 6(a) labels the boundary of the polarization mode switching, the region above (below) the dashed line is for the YP (XP) mode, which plays the dominant role. It should be pointed out that, for the region in which the feedback strength is too small, the feedback from the FBG cannot drive the VCSEL into a chaotic state, and the VCSEL operates at a quasi-periodic state. In this case, the value of $\sigma$ is relatively large and more than 0.7 (marked by orange and red). Except that the output of the FBGF-VCSEL is in chaos. As shown in Fig. 6(a), the TDS suppressed ($\sigma < 0.1$) parameter areas are mainly concentrated in two regions, where one is for $3 \text{ mA} < I < 3.1 \text{ mA}$, $0.04 < \xi_f < 0.20$, and the other is for $3.9 \text{ mA} < I < 4.1 \text{ mA}$, $0.12 < \xi_f < 0.34$. In the former region, the XP mode plays a dominant role and locates at the left edge of main lobe of FBG reflection spectrum, where the group velocity dispersion is strong. Such group delay introduced by FBG feedback broadens the time-delay peak in the ACF, and thus the TDS is suppressed well. For the latter, the YP mode will always play a dominant role because the YP mode of the solitary VCSEL locates within the main lobe of FBG reflection spectrum [shown in Fig. 5(a3)]. After further taking into account the FBG feedback, the YP mode will shift to the right edge of main lobe of FBG reflection spectrum due to feedback-induced. Under this circumstance, the TDS of chaos can be effectively suppressed due to the strong dispersion of the right edge of main lobe of FBG. In addition, for comparison, the TDS $\sigma$ of MF-VCSEL is also presented in Fig. 6(b). Different from the case for FBGF-VCSEL, the YP mode always plays the dominant role in MF-VCSEL; therefore, the polarization mode switching has not been observed. Meanwhile, the TDS of MF-VCSEL is relatively obvious, and no region of $\sigma < 0.1$ can be observed, which is attributed to the fact that the mirror cannot offer frequency selective feedback.

4. CONCLUSION

In summary, the TDS of chaotic output from an FBGF-VCSEL has been experimentally investigated. The results show that the feedback strength $\xi_f$ and the bias current $I$ are two key parameters for TDS suppression in FBGF-VCSEL. Under our experimental conditions, two optimal TDS suppressed regions with $\sigma < 0.1$ mainly distributed in $3 \text{ mA} < I < 3.1 \text{ mA}$, $0.04 < \xi_f < 0.20$, and $3.9 \text{ mA} < I < 4.1 \text{ mA}$, $0.12 < \xi_f < 0.34$, where the dominant polarization mode locates at the edge of the main lobe of FBG reflection spectrum. Moreover, through comparing the TDS of chaotic output from an MF-VCSEL, the FBGF-VCSEL shows an obvious advantage in suppressing the TDS of chaos. We hope this work may be helpful for VCSEL-based high-dimension TDS-suppressed optical chaos signal generation and relevant applications.

Funding. National Natural Science Foundation of China (NSFC) (61178011, 61275116, 61475127, 61575163); Fundamental Research Funds for the Central Universities (XDJK2016D060).

REFERENCES


