AIP Chaos
An Interdisciplinary Journal of Nonlinear Science
25TH ANNIVERSARY

Chaos synchronization in vertical-cavity surface-emitting laser based on rotated polarization-preserved optical feedback

Salam Nazhan, Zabih Ghassemlooy, and Krishna Busawon

Citation: Chaos **26**, 013109 (2016); doi: 10.1063/1.4940766
View online: http://dx.doi.org/10.1063/1.4940766
View Table of Contents: http://scitation.aip.org/content/aip/journal/chaos/26/1?ver=pdfcov
Published by the AIP Publishing

CHAOS 26, 013109 (2016)

Chaos synchronization in vertical-cavity surface-emitting laser based on rotated polarization-preserved optical feedback

Salam Nazhan, Zabih Ghassemlooy, and Krishna Busawon
Optical Communications Research Group, NCRLab, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, United Kingdom

(Received 9 May 2015; accepted 5 January 2016; published online 22 January 2016)

In this paper, the influence of the rotating polarization-preserved optical feedback on the chaos synchronization of a vertical-cavity surface-emitting laser (VCSEL) is investigated experimentally. Two VCSELs' polarization modes (XP) and (YP) are gradually rotated and re-injected back into the VCSEL. The anti-phase dynamics synchronization of the two polarization modes is evaluated using the cross-correlation function. For a fixed optical feedback, a clear relationship is found between the cross-correlation coefficient and the polarization angle θ_p. It is shown that high-quality anti-phase polarization-resolved chaos synchronization is achieved at higher values of θ_p. The maximum value of the cross-correlation coefficient achieved is -0.99 with a zero time delay over a wide range of θ_p beyond 65° with a poor synchronization dynamic at θ_p less than 65°. Furthermore, it is observed that the antiphase irregular oscillation of the XP and YP modes changes with θ_p. VCSEL under the rotating polarization optical feedback can be a good candidate as a chaotic synchronization source for a secure communication system. © *2016 AIP Publishing LLC*.
[http://dx.doi.org/10.1063/1.4940766]

We have experimentally shown that vertical-cavity surface-emitting laser (VCSEL) can produce high-quality anti-phase polarization-resolved chaos synchronization between their polarization modes (XP and YP) under rotating polarization-preserved optical feedback (RPPOF). Furthermore, we show that a different chaotic dynamics can be achieved by means of rotated-polarization OF, which indicates a complex dynamic behavior associated with the rotated polarization angle. A high anti-phase cross-correlation value (-0.99) between the polarization modes of the VCSEL has achieved experimentally with zero time delay between the synchronized signals.

I. INTRODUCTION

Chaotic systems with a number of unique features, including a noise-like shape with a broadband spectra, lower power implementations, and nonlinearity, have become appealing for modern secure communications applications. In such systems, a message is encoded into a noise like signal generated by a laser source with the chaotic behavior.[1] In the recent years, chaos synchronization has become a hot topic due to their potential applications in optical communication systems where security is paramount. Synchronization of chaos has attracted increasing attention specially in coupled VCSELs with a polarization-rotated optical feedback (OF) and optical injection.[2,3] One of the important applications of the synchronized chaotic system is for encrypted communications, where the chaotic dynamic of an optical laser is controlled through both synchronization phenomena and the polarization-rotated OF. Chaotic operation in semiconductor laser sources can be achieved using an external OF and optical injection,[2,4] even more with free running operating semiconductor lasers.[5] Several theoretical and experimental studies have reported that the dynamics of polarization-rotated OF[6] in a semiconductor laser is quite different from the conventional OF.[5,7,8] Our recent works have employed the rotated polarization optical feedback to suppress the polarization nonlinearity[9] and polarization switching (PS) in VCSEL with the modulation signal.[10]

In a number of applications such as communication systems, high pump sources, and optical fiber systems, a potential light source that could be adopted is the VCSEL with unique features including high data rates,[11] low power consumption, and lower manufacturing costs.[12] VCSELs are sensitive to the OF and optical injection due to their higher mirror reflectivity inside the laser cavity.[3,13] However, OF does lead to a number interesting complex dynamic behaviors in VCSELs including chaotic, time-period pulsing dynamics, and PS.[14,15] In the past few years, the chaotic dynamics of VCSELs with OF has been the subject of interest by researchers both theoretically and experimentally[2,16] particularly for secure optical-based communication systems. Recently, synchronization of the orthogonal polarization modes of VCSEL received wide attention as a chaotic source in secure communication systems.[17,18] In VCSELs, detailed characteristics of chaos synchronization outlined in Ref. 15 showed that the anti-phase chaotic synchronization can be achieved between orthogonal polarization modes of the two mutually coupled VCSELs. A solitary VCSEL can exhibit strong anti-phase dynamics between orthogonal polarization modes.[18] Numerically and experimentally study in Ref. 11 outlined that the two polarization modes of VCSEL exhibit anticorrelated dynamics with OF. However, a study presented an anti-phase oscillation between transverse electric (TE) and transverse magnetic (TM) modes in a semiconductor laser with polarization-rotated OF.[19] Maximum values

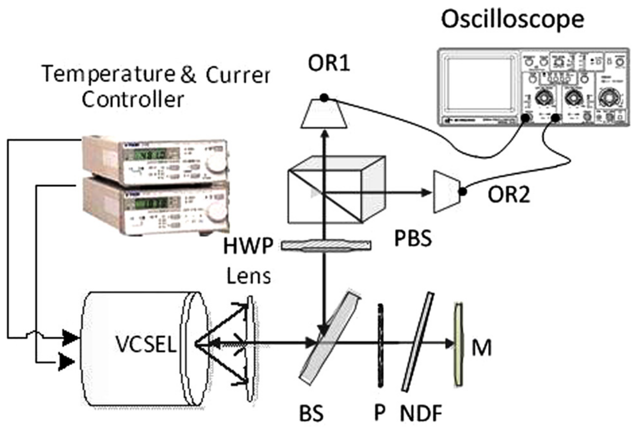

FIG. 1. The experimental setup of the VCSEL for the chaotic dynamics measurements.

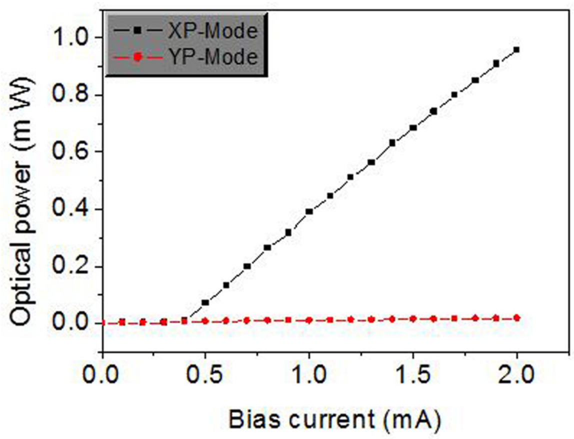

FIG. 2. Polarization-resolved L-I curve of the solitary VCSEL. Square black and dotted red lines correspond to the XP and YP modes, respectively.

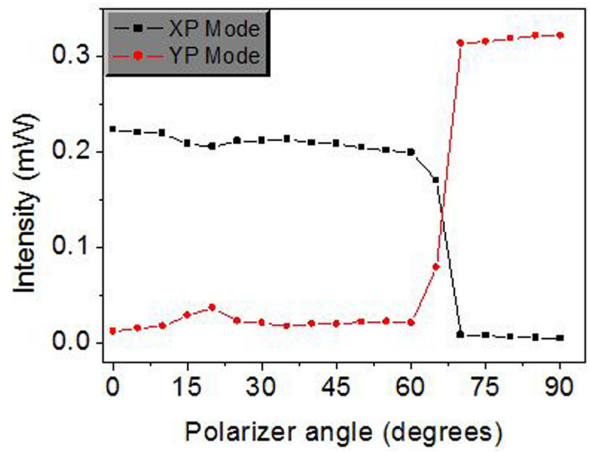

FIG. 4. Polarization-resolved intensities as functions of polarizer angle for $I_B = 1.2$ mA and with an OF level of −7.4 dB.

for the correlation coefficient of the synchronization modes of −0.68 and −0.99 obtained experimentally and theoretically, respectively, with a zero time lag between the orthogonal modes under appropriate conditions have been reported.[19] An anti-phase synchronization phenomenon is a common feature in semiconductor lasers with polarization rotated OF technique. Furthermore, the time lag between the two synchronization signals can be zero in complete chaos synchronization.[20]

To best of our knowledge, no experimental works have been reported on the high quality of a chaotic synchronization between the orthogonal polarization modes of VCSEL with a correlation coefficient of −0.99 and a zero time delay. We have experimentally shown that VCSEL can produce high-quality anti-phase polarization-resolved chaos synchronization between the X and Y polarisation modes (XP and YP) under RPPOF. Furthermore, we show that a different chaotic pattern can be achieved by means of rotated-polarization OF, which indicates the complex dynamic behaviour associated with the rotated polarization angle.[7] The anti-phase correlation of a semiconductor laser was experimentally observed in Ref. 7 for the case where the chaotic oscillation of the polarization modes was lower than the relaxation oscillation frequency.

The remainder of this paper is organized as follows: In Section II, the experimental setup is outlined. In Section III, the main results and discussion are presented, and more specifically, the chaotic synchronization of the XP and YP modes with a rotated-polarization angle of the OF is outlined. Finally, in Section IV, concluding remarks are provided.

II. EXPERIMENTAL SETUP

To investigate the influences of RPPOF on the chaotic dynamics properties of the VCSEL, we have adopted the following experimental set-up as showed in Fig. 1.

We have used a commercial single mode 852 nm VCSEL with a linear optical light–current (L-I) characteristic over a

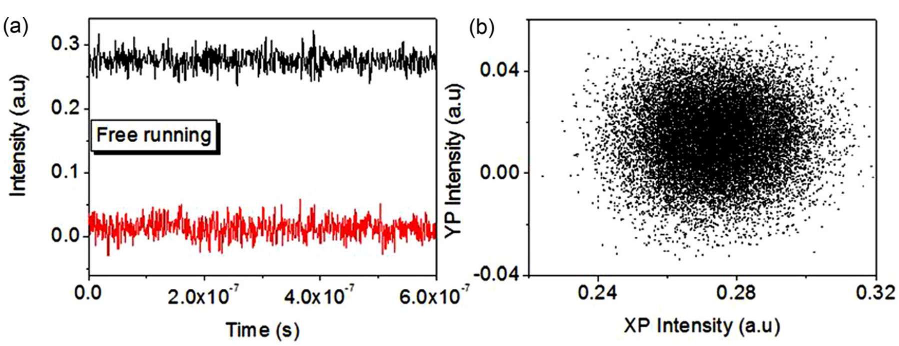

FIG. 3. (a) Polarization-resolved time series of the VCSEL modes (XP (black) and YP (red)) at free running and (b) the corresponding correlation profile.

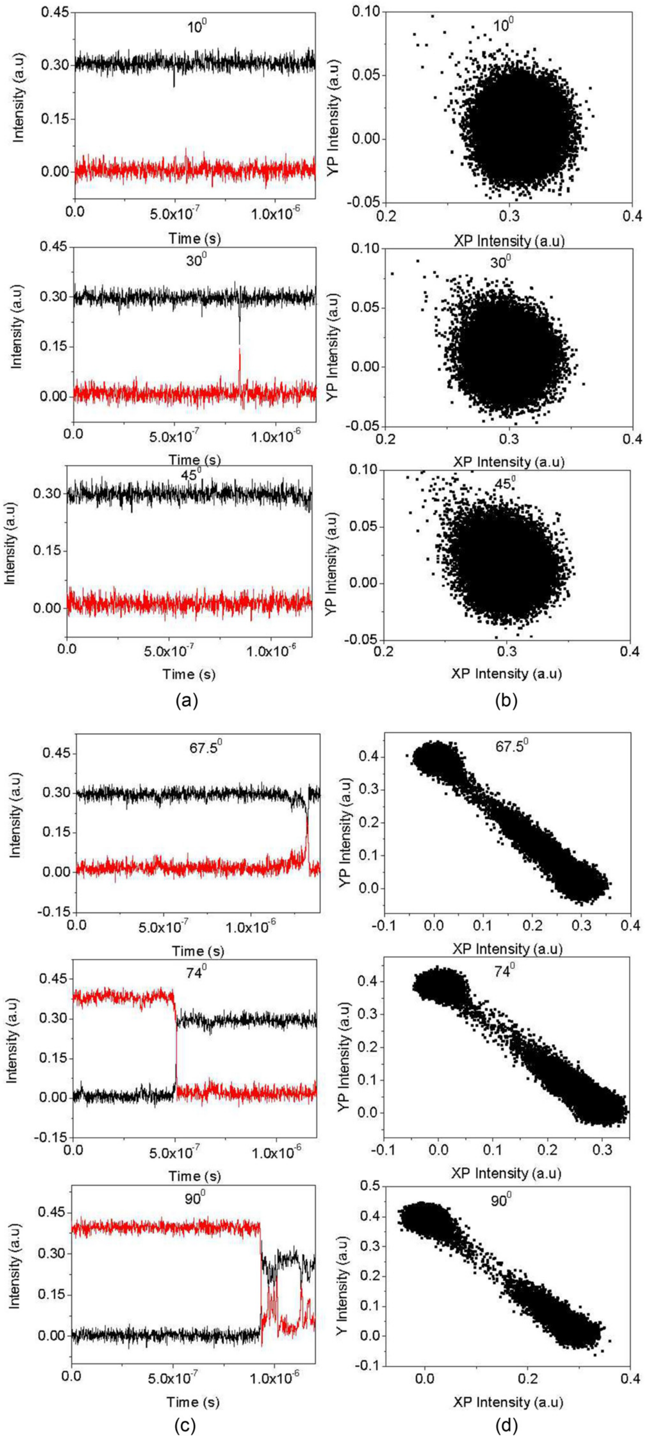

FIG. 5. (a) and (c) Polarization-resolved time series of the polarization modes of the VCSEL, XP (black) and YP (red) at a bias current of 1.2 mA and −7.4 dB of a feedback level: (a) for θ_p of 10°, 30°, and 45°, (c) for θ_p of 67.5°, 74°, and 90°, (b) and (d) corresponding correlation plots for (a) and (c), respectively.

range of bias current I_B. The VCSEL is driven by the laser diode driver module (Newport, 505B) and is temperature controlled using a thermoelectric temperature controller (TED 200C) to within 0.01 °C. The laser output beam is first collimated using an objective lens before being passed through a 50/50 non polarizer beam splitter (PBS), which is used to direct ∼50% of VCSEL's output power to a mirror (M). A polarizer (P) is used to implement RPPOF. A neutral density filter (NDF) is employed to adjust the OF level. A half wave plate (HWP) and a PBS are used to direct the orthogonal polarizations modes to two identical optical receivers (ORs). The outputs of ORs are then captured and stored in a digital oscilloscope (Agilent, DSO9254A, 20GS$_a$/s) for further off-line analysis.

The optical output power of the VCSEL is measured using an optical power meter (Anritsu, ML9001A). The external cavity length was set to be ∼26 cm, which corresponds to a feedback time of 1.7 ns. The solitary VCSEL lases' in the fundamental mode with two orthogonal polarization modes of XP and YP for the entire range of I_B (0–2 mA). The maximum measured output power of the VCSEL is 0.95mW at I_B of 2 mA.

III. RESULTS AND DISCUSSION

The polarization-resolved L-I characteristics of the free running VCSEL at a room temperature of 20 °C are shown in Fig. 2. From this figure, it can be seen that the XP mode begins to oscillate when I_B is ∼0.5 mA, which is the dominant mode and with no PS being observed over the entire range of I_B. The power of the XP mode increases linearly, and the YP mode is entirely suppressed over the I_B range. In fact, VCSEL's instabilities are also dependent on the injection current with PS between the polarization modes when I_B is increased.[10] Furthermore, the dynamics of the oscillation modes is strongly anti-correlated.[21] In this work, we have set I_B at 1.2 mA for all the measurement campaign. The VCSEL lases in two orthogonal polarization modes (XP and YP) under the same ambient conditions, but displays a quite different behaviour.

Mode competition between the two VCSEL's modes could result in anti-correlated dynamics of modes oscillations.[3] Fig. 3 shows the polarization-resolved time series of the XP mode (upper, black) and the YP mode (lower, red) of the free running VCSEL. The intensity of the XP and YP modes for the free running VCSEL is shown in Fig. 3(a), where the XP mode displays higher intensity levels (0.27 (arb.unit)) compared with the YP mode (0.013 (arb.unit)). The corresponding correlation plot is depicted in Fig. 3(b), confirming no chaotic synchronization being observed

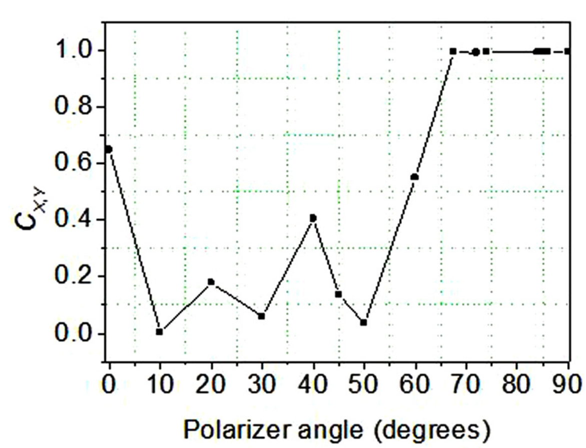

FIG. 6. The absolute value of the correlation coefficient $C_{x,y}$ of the two polarization modes as a function of the polarizer angle.

between the two polarizations modes under free running condition.

A. Influence of RPPOF on the VCSEL dynamics

Next, we investigate RPPOF effects on the chaotic dynamic of VCSEL when rotating θ_p. It should be noted that the case of $\theta_p = 0°$ and $\theta_p = 90°$ corresponds to pure XP and YP feedbacks, respectively. The normalized polarization-resolved intensities as a function of the polarization angle are illustrated in Fig. 4 for a fixed OF level of −7.4 dB. The YP mode is highly suppressed for $\theta_p \leq \sim 65°$ with slight hump at θ_p of 20°, while the XP mode is the dominant for $\theta_p \leq 65°$. At θ_p of ∼65°, the VCSEL displays abrupt PS between the XP and YP modes. For $\theta_p \geq \sim 70°$, the XP mode is entirely suppressed with much reduced optical power of 0.004 mW, while the YP is the dominant mode with an increased optical power of 0.32 mW. Here, for the sake of illustrating the concept, we will consider θ_p from 0° to 90°.

Figure 5 shows the time series and the corresponding correlation plots for an OF level of −7.4 dB. For $\theta_p \leq 45°$, Figs. 5(a) and 5(b), it can be observed that the XP mode exhibits higher intensity signal level compared with the YP mode with almost no synchronization between the oscillation modes. At $\theta_p \leq 45°$, both the XP and YP modes initiate chaotic states of synchronization as can be seen from scatters points in the correlation plots, but with a low level of correlation, which will be discussed later in Section IV. Both XP and YP modes display stable intensity profiles with no fluctuation over the entire time series range, see Fig. 5(a).

Fig. 5(b) depicts that there is no synchronization between the orthogonal modes for $\theta_p \leq 45°$. However, as θ_p increases beyond ∼65°, the results show an interesting dynamic behaviour with higher intensity fluctuations as well as PS between the XP and YP modes. The corresponding correlation plots for θ_p of 67.5°, 74°, and 90° display a perfect anti-phase chaotic synchronization profile between the XP and YP modes over the time series range. The maximum absolute value obtained for θ_p beyond 65° of the correlation coefficient is 0.99 with a zero time the shift of the anti-phase dynamics. The laser modes dynamics could follow the instantaneous gain change between the two laser modes fluctuation near by the PS point.[14] The enhanced results obtained for the anti-phase chaotic synchronization can be attributed to the gain fluctuations close to the PS position of the two orthogonal polarization modes of the VCSEL.

On the other hand, when $\theta_p > 45°$, the XP mode loses OF while the YP mode experiences more OF, thus resulting in PS and for the YP becoming the dominant mode.[22]

A strong anti-phase dynamics in VCSELs might be responsible for the high-quality of the anti-phase dynamics synchronization of VCSEL.[18] The results reveal that with RPPOF one can achieve high quality anti-phase chaotic oscillation synchronization for θ_p higher than 65°.

The measured cross-correlation coefficient can be used to evaluate the synchronization statues of the two systems. The sampling rate used for the calculation of the cross-correlation coefficient is 5.0057×10^4, which is also used for evaluating the anti-phase correlation profile. The correlation coefficient $C_{x,y}$ for the XP and YP modes for evaluating the anti-phase chaotic synchronizations is given by[23]

$$C_{x,y} = \frac{\left[I_x(t) - I_x(t)\right]\left[I_y(t-\tau) - I_y(t)\right]}{\sqrt{\left[I_x(t) - I_x(t)\right]^2 \left[I_y(t) - I_y(t)\right]^2}},$$

where $I_x(t)$ and $I_y(t)$ are the intensity outputs of the XP and YP modes, respectively; the term <·> is the mean value, and τ is the time delay. The absolute values of $C_{x,y}$ between

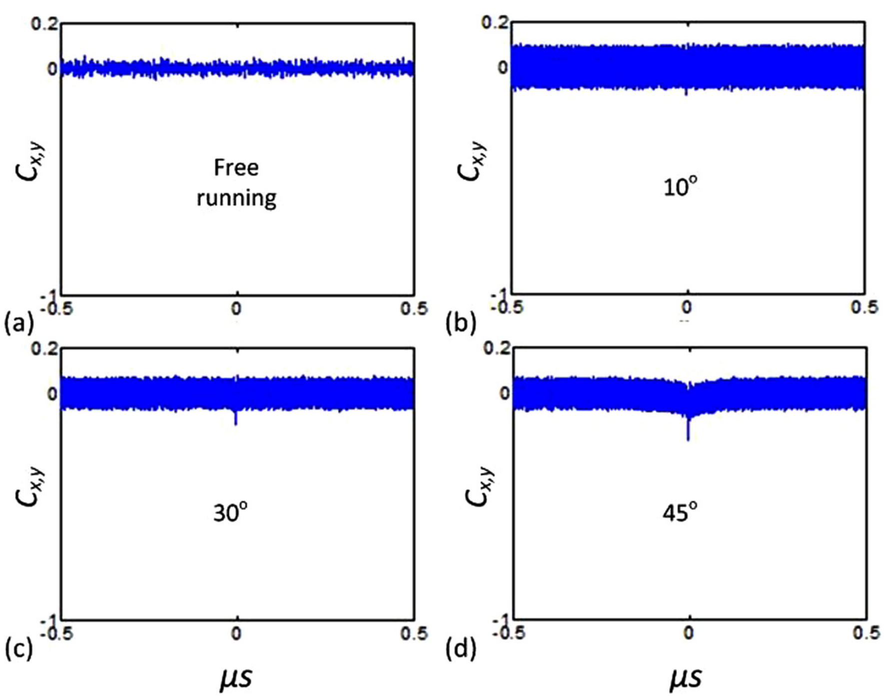

FIG. 7. The cross-correlation coefficient $C_{x,y}$ as a function of the intensity time traces of the XP and YP modes for (a) free running, and θ_p of (b) 10°, (c) 30°, and (d) 45°.

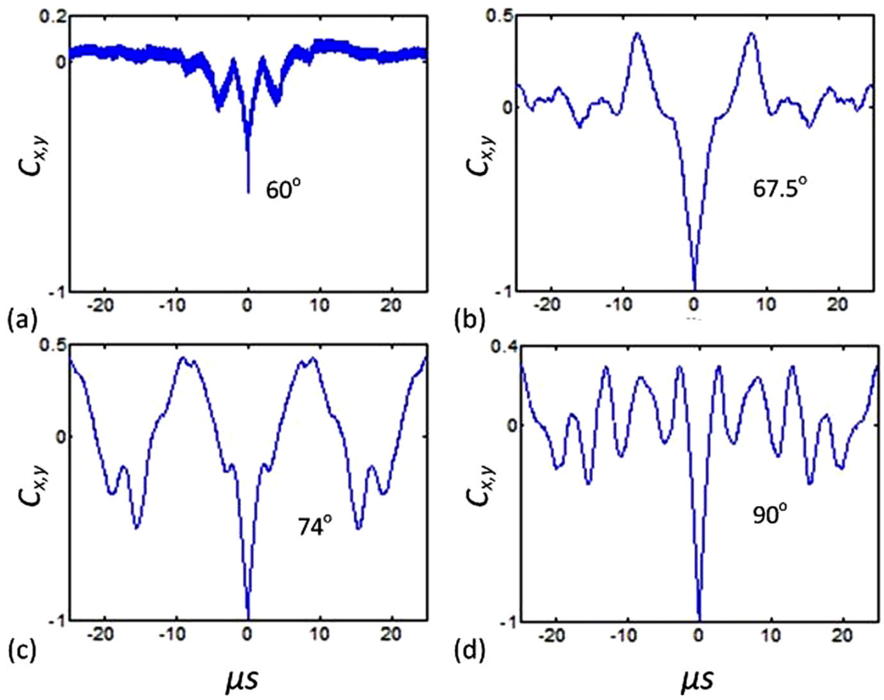

FIG. 8. The cross-correlation coefficient $C_{x,y}$ as a function of the intensity time traces of the XP and YP modes for the polarization angles of 60°, 67.5°, 74°, and 90°.

the two oscillation modes as a function of polarizer angle are presented in Fig. 6. Over the range of θ_p between 0° and ∼60°, $C_{x,y}$ values are relatively low, thus resulting in lower anti-phase synchronization between the XP and YP modes. However, for $\theta_p > \sim 60°$, a higher value of 0.99 is achieved for $C_{x,y}$.

The results outlined above clearly demonstrate the high quality of anti-phase chaotic synchronization with $C_{x,y}$ of 0.99 and a zero time delay between the two orthogonal polarization modes of the VCSEL, which to the best of our knowledge is the first experimental data being reported. Furthermore, we have shown how the anti-phase chaotic synchronization depending on the rotated polarization angle of the OF.

Fig. 7 illustrates dependence $C_{x,y}$ on the time shift of one of the modes (i.e., YP) for the free running operation and a range of θ_p of 10°, 30°, and 45°, respectively. The $C_{x,y}$ confirm our previous observations in Figs. 5 and 6 on the dynamic features of the XP and YP modes as a function of θ_p.

Finally, Fig. 8 displays $C_{x,y}$ in the time window for the XP and YP modes for θ_p of 60°, 67.5°, 74°, and 90°. The plots not only confirm our previous observations on the dynamics of the XP and YP modes for $\theta_p > 45°$ but also display different peak values for $C_{x,y}$. Higher values of $C_{x,y}$ are observed at θ_p of 67.5°, 74°, and 90° in line with Fig. 6.

IV. CONCLUSIONS

We have experimentally demonstrated the possibility of high-quality anti-phase chaotic synchronization between the two polarization modes of VCSEL under rotated-polarization preserved optical feedback. An evaluation of the anti-phase chaotic synchronization was carried out with RPPOF using based on the cross-correlation function matrix. The time series of the XP and YP modes showed a perfect anti-phase chaotic synchronization for θ_p larger than 65°. For high values of θ_p, the XP and YP modes displayed strong fluctuations and showed close similarity to each other, thus resulted in high quality anti-phase synchronization. We showed that there is a clear relationship between $C_{x,y}$ and θ_p. It was also shown that high anti-phase synchronization was achieved under the mode intensity fluctuation. It was observed that the antiphase dynamics of the XP and YP modes changed with θ_p. The results shown confirm that VCSEL with RPPOF can be adopted as a chaotic light source in secure communication systems.

ACKNOWLEDGMENTS

The author Salam Nazhan is gratefully acknowledged his sponsors, Ministry of Higher Education and Scientific Research of Iraq (MOHESR) and Diyala University, Iraq for support his Ph.D. study.

[1]N. Jiang, W. Pan, L. Yan, B. Luo, X. Zou, S. Xiang, L. Yang, and D. Zheng, IEEE Photonics Technol. Lett. **22**(10), 676 (2010).
[2]J. Liu, Z.-M. Wu, and G.-Q. Xia, Opt. Express **17**(15), 12619 (2009).
[3]N. Fujiwara, Y. Takiguchi, and J. Ohtsubo, Opt. Lett. **28**(18), 1677 (2003).
[4]J. Ohtsubo, IEEE J. Quantum Electron. **38**(9), 1141 (2002); S. F. Yu, *ibid.* **35**(3), 332 (1999).
[5]M. Virte, K. Panajotov, H. Thienpont, and M. Sciamanna, Nat. Photonics **7**(1), 60 (2013).
[6]Y. Takeuchi, R. Shogenji, and J. Ohtsubo, Opt. Rev. **17**(5), 467 (2010).
[7]T. Heil, A. Uchida, P. Davis, and T. Aida, Phys. Rev. A **68**(3), 033811 (2003).
[8]N. Shibasaki, A. Uchida, S. Yoshimori, and P. Davis, IEEE J. Quantum Electron. **42**(3), 342 (2006).
[9]S. Nazhan, Z. Ghassemlooy, K. Busawon, and A. Gholami, IEEE Photonics Technol. Lett. **28**(2), 185 (2016).
[10]S. Nazhan, Z. Ghassemlooy, K. Busawon, and A. Gholami, Opt. Laser Technol. **75**, 240 (2015).

[11]S. A. Blokhin, J. A. Lott, A. Mutig, G. Fiol, N. N. Ledentsov, M. V. Maximov, A. M. Nadtochiy, V. A. Shchukin, and D. Bimberg, Electron. Lett. **45**(10), 501 (2009).
[12]J.-W. Shi, Z.-R. Wei, K.-L. Chi, J.-W. Jiang, J.-M. Wun, I. Lu, J. J. Chen, and Y.-J. Yang, J. Lightwave Technol. **31**(24), 4037 (2013).
[13]K. Panajotov, M. Sciamanna, M. A. Arteaga, and H. Thienpont, IEEE J. Sel. Top. Quantum Electron. **19**(4), 1700312 (2013).
[14]R. Michalzik, *VCSELs: Fundamentals, Technology and Applications of Vertical-Cavity Surface-Emitting Lasers* (Springer Berlin Heidelberg, Berlin, Heidelberg, 2013).
[15]S.-Y. Lin, Y.-C. Su, Y.-C. Li, H.-L. Wang, G.-C. Lin, S.-M. Chen, and G.-R. Lin, Opt. Express **21**(21), 25197 (2013).
[16]Y. Hong, P. Spencer, and K. Shore, IEEE J. Quantum Electron. **50**(4), 236 (2014).
[17]M. Ozaki, H. Someya, T. Mihara, A. Uchida, S. Yoshimori, K. Panajotov, and M. Sciamanna, Phys. Rev. E **79**(2), 026210 (2009).
[18]A. Uchida, H. Someya, M. Ozaki, K. Tanaka, S. Yoshimori, K. Panajotov, and M. Sciamanna, paper presented at the IEEE/LEOS Winter Topicals Meeting Series, 2009.
[19]Y. Takeuchi, J. Ohtsubo, and R. Shogenji, Appl. Phys. Lett. **93**(18), 181105 (2008).
[20]J. Ohtsubo, *Semiconductor Lasers: Stability, Instability and Chaos* (Taylor & Francis, 2006).
[21]K. Panajotov and F. Prati, *VCSELs* (Springer, 2013), p. 181.
[22]S. Xiang, W. Pan, L. Yan, B. Luo, N. Jiang, and L. Yang, Appl. Opt. **48**(27), 5176 (2009).
[23]I. Gatare, M. Sciamanna, A. Locquet, and K. Panajotov, Opt. Lett. **32**(12), 1629 (2007).