ABSTRACT

A scheme for generating wideband optical frequency comb (OFC) is proposed and experimentally investigated based on a master-slave system. In such a system, a tunable optical resource and a distributed feedback semiconductor laser are utilized as master lasers (MLs), and their outputs provide dual optical injection (DOI) into a slave laser (SL) which is a 1550 nm multi-transverse mode vertical-cavity surface-emitting laser (1550 nm-VCSEL) operating at gain-switched state. For the 1550 nm-VCSEL biased at a relatively high current, two low-order transverse modes $L_{01}$ and $L_{11}$ can simultaneously lase and possess comparable powers. After loaded a large signal modulation, the 1550 nm-VCSEL can be driven into gain-switched state, and two separated sub-combs originating from two transverse modes can be generated. Through further introducing DOI to the gain-switched 1550 nm-VCSEL, the two sub-combs can link up to form an overall OFC under suitable operation parameters. The experimental results show that, through selecting optimized operating parameters, the bandwidth of the integral OFC within 10 dB amplitude variation can achieve 150.0 GHz. Additionally, the effects of the wavelengths of the two injection lights on the bandwidth of the overall OFC are also analyzed.

INDEX TERMS
Optical frequency comb, multi-transverse mode vertical-cavity surface-emitting laser, gain-switched, dual optical injection.

I. INTRODUCTION

The globalization of information has led to a continuous increase of communication data and then brought a tremendous pressure on existing optical networks. Relevant researches predict that the internet traffic usage will achieve zettabyte ($10^{21}$) by 2021 [1]. In order to satisfy the demand of the growing capacity, it is urgently needed to exploit multi-carrier spectrally efficient transmission techniques, such as optical orthogonal frequency division multiplex (OFDM) [2]–[4], coherent wavelength division multiplexing (WDM) [5], WDM passive optical network (WDM-PON) [6], [7], and Nyquist WDM [8] etc. In multi-carrier transmission systems, an optical frequency comb (OFC) source is a key component. An OFC is an optical spectrum composed of a series of equi-spaced discrete spectral lines [9]. Various methods for generating OFC have been reported such as mode-locking lasers (MLLs) [10], [11],
micro-ring resonators [12], [13], electro-optic modulators (EOMs) [14]–[16], and gain-switched lasers [17], [18]. Each one has its own unique virtues and some room for improvement. For example, MLLs can generate stable and ultra-broadband OFC, but the spacing of comb lines is hard to be tuned. Micro-ring resonators are capable of generating stable wideband OFC, but the fluctuations in amplitude are difficult to avoid. EOMs can produce ultra-broadband OFC with tunable comb line spacing, but the modulator introduces large insertion loss. Comparatively, the OFC generation scheme based on gain-switched lasers has attracted enormous attention due to its easy implementation, stability, controllable repetition rate, cost effectiveness, and high flexibility.

In recent years, OFC generated by gain-switched edge-emitting lasers (EELs) has been studied extensively [19]–[24]. Zhou et al. proposed an experimental system for generating OFC based on a gain-switched Fabry-Pérot (FP) laser with externally optical injection, and demonstrated that a wavelength tunable OFC with 14–16 comb lines (around 160 GHz) within 3 dB amplitude variation can be obtained [22]. Subsequently, they experimentally investigated the gain-switched FP laser with dual mode injection locking, and obtained a wavelength tunable and highly coherent OFC with 52 comb lines (around 325 GHz) within 6 dB amplitude variation [23]. Zhu et al. theoretically and experimentally reported that expanded OFC with 54 spectral lines (around 540 GHz) within 10 dB amplitude variation was generated by an externally injected gain-switched distributed feedback (DFB) semiconductor laser after introducing a phase modulator [24]. In addition, as one type of semiconductor lasers, vertical-cavity surface-emitting laser (VCSEL) with gain-switching has been considered as a promising candidate for OFC generation due to its unique merits [25]–[27], and some efforts have been devoted to achieve high-quality OFC [28]–[33]. Criado et al. experimentally reported for the first time that a flat OFC with 20 comb lines (spaced by 4.2 GHz) within a 3 dB bandwidth can be generated by a commercial gain-switched VCSEL [28]. Prior et al. experimentally investigated the dynamics of dual-polarization OFC based on a gain-switched VCSEL with optical injection locking, and obtained an overall comb formed by two orthogonally polarized sub-combs, and further elaborated that the polarization state of the overall comb can be controlled by adjusting the polarization state of the injected light [29]. Quirce et al. theoretically investigated the OFC generated by a gain-switched VCSEL with polarized optical injection, and analyzed the effect of linear birefringence on the optical span of overall OFC combined by two orthogonally polarized sub-combs [30]. We have noticed that the generated schemes for OFC based on gain-switched VCSELs mentioned above almost focused on the case of VCSELs operating at single transverse mode. Nevertheless, when VCSELs are biased at relatively large currents, multiple transverse modes can be simultaneously stimulated owing to the spatial-hole burning effect [34], [35] and have been widely used in short-reach links, mode-division multiplexing, and high-performance computing [36]–[38]. In principle, under multiple optical injection, the output from a gain-switched multi-transverse mode VCSEL can achieve multiple expanded sub-combs provided by each transverse mode. When adjacent expanded sub-combs can link up and possess comparable intensities, an OFC with wider bandwidth can be obtained. Compared with single optical injection, adopting multiple optical injection is more favorable for increasing the number of comb lines within a given bandwidth.

Based on above analyses and considerations, a scheme for generating wideband OFC by using a gain-switched multi-transverse mode VCSEL subject to dual optical injection (DOI) is proposed and experimentally investigated. In the scheme, a gain-switched multi-transverse mode VCSEL is taken as slave laser (SL), in which two low-order transverse modes of LP_{01} and LP_{11} can simultaneously emit. Through further introducing DOI with optimized parameters, an OFC with a bandwidth beyond 150.0 GHz within 10 dB amplitude variation can be generated by comprising two sub-combs originating from LP_{01} and LP_{11}.

II. EXPERIMENTAL SETUP

Figure 1 is a schematic of experimental setup. A tunable laser (Santec, TSL-710, 1480 nm-1640 nm) and a commercial 1550 nm DFB semiconductor laser are used as master laser 1 (ML1) and master laser 2 (ML2), respectively, and a commercial 1550 nm multi-transverse mode VCSEL (Raycan) is utilized as slave laser (SL) in this experiment. The light emitted from ML1 is injected into the SL after passing through a polarization controller (PC1), a 10/90 fiber coupler (FC1), FC3, an optical isolator (OI) (isolation >55 dB), and a three-port optical circulator (OC) successively. Similarly, the output of ML2 is also injected into the SL after passing through PC2, an erbium doped fiber amplifier (EDFA), a variable attenuator (VA), FC2, FC3, OI, and OC. The injection powers of the two channels can be monitored by an optical power meter (PM) through the 10% part of the FC1 and FC2, respectively. PC1 and PC2 are employed to match the polarizations among ML1, ML2, and SL. The bias current and temperature of the SL are controlled by a high accuracy and
low noise current-temperature controller (ILX-Lightwave, LDC-3724C). During the experimental process, the SL temperature is stabilized at 19.20°C. A microwave frequency synthesizer (MFS, Agilent E8257C) provides a sinusoidal modulation signal, which is combined with the bias current via a bias tee. The output of the SL is sent to a detection system after passing through OC, FC4, FC5. An optical spectrum analyzer (OSA, Aragon Photonics BOSA lite+) with a 20 MHz resolution is utilized to observe the optical spectrum. The time series is recorded by a digital oscilloscope (OSC, Agilent DSO-X 91604A, 16 GHz bandwidth) after being converted into an electric signal by a photo-detector (PD1, New Focus, 1544-B, 12 GHz bandwidth).

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. OUTPUT CHARACTERISTICS OF THE SOLITARY SL

In order to describe the basic characteristics of the solitary SL, Fig. 2 shows the experimentally measured power-current curves and the optical spectrum when the SL is biased at 10.30 mA, in which the insets are the beam profiles captured by a CCD. Obviously, the threshold current of the SL is around 3.40 mA, from which one transverse mode begins to emit. According to its beam distribution, we can judge that it is the fundamental transverse mode (LP$_{01}$). Continuously increasing the bias current, the optical power of LP$_{01}$ mode gradually increases. When the bias current arrives at 7.71 mA, another transverse mode also emits, which is confirmed to be the first-order transverse mode (LP$_{11}$) by its distribution of the beam profile. The reason for the emission of LP$_{11}$ mode can be attributed to the spatial-hole burning effect (SHB) [34], [35]. Further continuously increasing the current, the intensity of the LP$_{11}$ increases, which results in the decrease of the LP$_{01}$ intensity due to the sharing of the carriers between modes. For the SL biased at 10.30 mA, the optical spectrum (Fig. 2(b)) shows that there are two strong peaks located at 1547.952 nm and 1547.240 nm, which belong to LP$_{01}$ and LP$_{11}$ modes, respectively. The wavelength (frequency) interval of the two modes is approximately 0.712 nm (41.1 GHz), and corresponding linear birefringence is about 129.2 ns$^{-1}$. For LP$_{11}$ mode, the wavelength (frequency) separation between two orthogonal polarization components is about 0.324 nm (40.5 GHz), and corresponding linear birefringence is about 127.2 ns$^{-1}$. In the following discussion, to achieve comparable optical powers of the two transverse modes, the bias current of the SL is set at 10.30 mA.

B. OUTPUT CHARACTERISTICS OF THE GAIN-SWITCHED SL

We first analyze the SL output under current modulation. The external modulation signal can be changed by adjusting the modulation intensity $P_m$ and the modulation frequency $f_m$. Figure 3 presents optical spectra (left column) and time series (right column) of the gain-switched SL under different modulation parameters ($P_m$, $f_m$). For ($P_m$, $f_m$) = (15.00 dBm, 2.5 GHz), the optical spectrum (as shown in Figs. 3(a1)) displays two sub-combs generated by the LP$_{01}$ and LP$_{11}$ modes, respectively, and the frequency interval of the adjacent comb lines for each sub-comb is 2.5 GHz. Further experimental results confirm that all the comb lines possess a parallel resolution of BOSA, only two dominant polarization components with parallel polarization in LP$_{01}$ and LP$_{11}$ have been observed. In fact, via a lower resolution OSA (Ando AQ6317C), two suppressed polarization components of LP$_{01}$ and LP$_{11}$ can be detected, which are located at 1548.281 nm and 1547.564 nm, respectively. As a result, the wavelength (frequency) separation between two orthogonal polarization components of the LP$_{01}$ mode is approximately 0.329 nm (41.1 GHz), and corresponding linear birefringence is about 129.2 ns$^{-1}$. For LP$_{11}$ mode, the wavelength (frequency) separation between two orthogonal polarization components is about 0.324 nm (40.5 GHz), and corresponding linear birefringence is about 127.2 ns$^{-1}$. In the following discussion, to achieve comparable optical powers of the two transverse modes, the bias current of the SL is set at 10.30 mA.

![FIGURE 2. Experimentally measured (a) power-current curves of solitary SL and (b) Optical spectrum of SL biased at 10.30 mA.](image)

![FIGURE 3. (a) Optical spectra and (b) time series of the gain-switched SL outputs under different modulation parameters ($P_m$, $f_m$), where ($P_m$, $f_m$) is (15.00 dBm, 2.5 GHz) (row 1), (20.00 dBm, 2.5 GHz) (row 2), and (20.00 dBm, 3.0 GHz) (row 3), respectively.](image)
polarization. As shown in Fig. 3(b1), the time series displays a regular pulse oscillation with a frequency of 2.5 GHz. Further increasing the modulation intensity to 20.00 dBm (as shown in Fig. 3(a2) and (b2)), the comb lines become indistinct, the timing jitter increases, and some pulses are not able to switch on. Under this case, the larger effect of spontaneous emission noise makes the frequency chirping more noisy and the comb lines in optical spectrum are lost, and meanwhile optical pulses switch-off to levels at which spontaneous emission noise dominates the evolution [39]. Moreover, the optical spectrum red-shift can be observed due to the heating effect resulted by the current modulation. For \((P_m, f_m) = (20.00 \text{ dBm}, 3.0 \text{ GHz})\), the optical spectrum (as shown in Figs. 3(a3)) indicates that the comb lines of two sub-combs become distinct again. The frequency interval between adjacent comb lines in each sub-comb is 3.0 GHz. From Fig. 3(b3), it can be seen that the time series displays a periodic pulse oscillation with a frequency of 3.0 GHz. These phenomena indicate that under suitable modulation parameters, the comb spacing of OFC generated by the gain-switched SL can be tuned, which has been confirmed in [39]. In the following experiment, the modulation frequency is fixed at 2.5 GHz.

C. OFC GENERATED BY THE GAIN-SWITCHED SL UNDER DOI

1) MODULATION INTENSITY \(P_m = 15.00 \text{ dBm}\)

For a gain-switched multi-transverse mode VCSEL under single optical injection, the sub-comb originated from the transverse mode near to the injection light will be enhanced while the sub-comb originated from other transverse modes will be weakened due to the mode selection. Therefore, in order to obtain wider bandwidth OFC, DOI is adopted in this work, and we will investigate the output of the gain-switched SL under DOI. The light emitted from ML1 (ML2) is named as the injection light 1 (injection light 2), and the corresponding wavelength and injection power is \(\lambda_1, P_{in1}\) and \(\lambda_2, P_{in2}\). During the experiment, the values of \(\lambda_1\) are controlled smaller than those of \(\lambda_2\). In the following, we take two cases of \(P_{in1} = 15.00 \text{ dBm}\) and \(P_{in2} = 20.00 \text{ dBm}\) as two examples to discuss the performances of the OFC generated by the gain-switched SL under DOI.

For the SL under the current modulation with \((f_m, P_m) = (2.5 \text{ GHz}, 15.00 \text{ dBm})\), we fix the injection parameters of the injection light 2 at \((P_{in2}, \lambda_2) = (0.65 \text{ mW}, 1548.564 \text{ nm})\) to inspect the output of the SL under the injection light 1 at \(P_{in1} = 0.78 \text{ mW}\) and different values of \(\lambda_1\), and the results are given in Fig. 4. In this work, the power flatness of OFC is characterized by the bandwidth (BW) defined as the continuous frequency range within which the power differences between the highest comb line and the others are not more than 10 dB. A larger BW means a better power flatness. For \(\lambda_1 = 1547.771 \text{ nm}\) (Fig. 4(a)), the optical spectrum shows two separated sub-combs originated from the LP_{01} and LP_{11} modes. The sub-comb of LP_{11} mode includes 14 comb lines within 10 dB bandwidth (the corresponding BW are approximately 32.5 GHz), and the sub-comb of LP_{01} mode includes 30 comb lines within 10 dB bandwidth (the corresponding BW are approximately 72.5 GHz).

For \(\lambda_1 = 1547.872 \text{ nm}\) as shown in Fig. 4(b), one can see that the sub-comb for LP_{01} mode distinctly decrease, and the BW is reduced to 27.5 GHz. It can be inferred that the parallel polarization component of LP_{11} mode is suppressed. In other words, polarization switching (PS) leads to a reduction of the BW and is near to the LP_{01}. Under this case, the injection light 1 results in the sub-comb originated from LP_{01} mode expanded to 40 comb lines (the corresponding BW of 97.5 GHz).

2) MODULATION INTENSITY \(P_m = 20.00 \text{ dBm}\)

Next, we will discuss the case that the SL under the current modulation with \((f_m, P_m) = (2.5 \text{ GHz}, 20.00 \text{ dBm})\). We fix the injection parameters of the injection light 2 at \((P_{in2}, \lambda_2) = (0.72 \text{ mW}, 1548.932 \text{ nm})\) and the power of the injection power of the injection light 1 at \(P_{in1} = 0.85 \text{ mW}\). Figure 5 presents the results under different \(\lambda_1\). For \(\lambda_1 = 1548.128 \text{ nm}\) (Fig. 5(a)), one can see that the orthogonal polarization component of LP_{11} mode emits the power of comb lines are uneven. The sub-comb of LP_{11} mode includes 18 comb lines and the BW is about 42.5 GHz. While the sub-comb of LP_{01} mode includes 18 comb lines and the BW is about 77.5 GHz. When \(\lambda_1\) is increased to 1548.208 nm (Fig. 5(b)), the intensities of...
orthogonal polarization component of the sub-comb for LP\textsubscript{11} mode increase. One can observe that a flat overall OFC with 60 comb lines linked by the sub-combs of LP\textsubscript{11} and LP\textsubscript{01} modes is formed, and the BW is approximately 147.5 GHz. Further increasing \(\lambda_1\) to 1548.304 nm (Fig. 5(c)), the intensities of parallel polarization component of sub-comb for LP\textsubscript{11} mode distinctly decrease, which makes the number of comb lines for the overall OFC reduce to 49 and the corresponding BW is 120.0 GHz. When \(\lambda_1\) is increased to 1548.382 nm (Fig. 5(d)), the intensities of parallel polarization component of sub-comb for LP\textsubscript{11} mode begin to increase. Moreover, due to the sharing of the carriers, the intensities of sub-comb originated from LP\textsubscript{01} mode drastically change, and the intensities of orthogonal polarization component sub-comb for LP\textsubscript{01} mode gradually decrease. As a result, the power flatness decreases significantly compared with Fig. 5(b), the comb lines of overall OFC drop sharply to 32 and the BW is about 77.5 GHz. Based on above experimental results, one can conclude that a wideband overall OFC generated by two sub-combs of LP\textsubscript{01} and LP\textsubscript{11} modes can be achieved by the gain-switched SL with DOI under appropriate injection parameters.

In addition, we also investigate the case that the injection parameters (\(P\textsubscript{in1}, \lambda_1\)) of the injection light 1 and the injection power (\(P\textsubscript{in2}\)) of the injection light 2 are fixed to certain values, while the wavelength (\(\lambda_2\)) of the injection light 2 is taken different values. For (\(P\textsubscript{in1}, \lambda_1\)) = (0.85 mW, 1548.272 nm) and \(P\textsubscript{in2} = 0.75\) mW, the optical spectra of the gain-switched SL subject to DOI under different \(\lambda_2\) are given in Fig. 6, where Fig. 6(a-d) are for \(\lambda_2 = 1549.012\) nm, 1548.934 nm, 1548.902 nm, and 1548.876 nm, respectively. From this diagram, one can observe that the evolutionary trend of optical spectra is similar to those of Fig. 5.

The above results show that, the interval of comb lines in each sub-comb is equal to the modulation frequency \(f_m\) and is independent of the optical injection. After adopting strong injection locking, the locations of comb lines are determined by the wavelength of injection light and the modulation frequency \(f_m\). Under injection light with a frequency of \(f_{inj}\), the comb lines will locate at \(f_{inj} \pm nf_m\) (n is integer), but the intensity of each comb line depends on almost all the system parameters. Under the other parameters given, the variations of the number of comb lines and BW for the overall OFC with the injection wavelength are displayed in Fig. 7. For the case of (\(P\textsubscript{in2}, \lambda_2\)) = (0.72 mW, 1548.932 nm) and \(P\textsubscript{in1} = 0.85\) mW as shown in Fig. 7(a), one can see that, for \(\lambda_1 < 1548.176\) nm, the number of comb lines and the BW remain constant, which indicates two sub-combs of LP\textsubscript{01} and LP\textsubscript{11} modes are independent two parts. Under these conditions, the BW of sub-comb originated from LP\textsubscript{01} mode is wider than that of LP\textsubscript{11} mode, and then the number of comb lines and the BW are represented by the sub-comb of LP\textsubscript{01} mode. For 1548.176 nm < \(\lambda_1 < 1548.288\) nm, the number of comb lines and the BW rapidly increase to a certain value, and then vary around the value, which manifests that the overall OFC is formed by two sub-combs of LP\textsubscript{01} and LP\textsubscript{11}.
modes. For $\lambda_1 > 1548.288$ nm, the number of comb lines and the BW gradually decrease, which shows that the power of overall OFC becomes uneven due to the PS induced by optical injection and the sharing of the carriers. For $(P_{in1}, \lambda_1) = (0.85$ mW, 1548.272 nm) and $P_{in2} = 0.75$ mW as shown in Fig. 7(b). With the decrease of $\lambda_2$, the varied trends of the number of comb lines and the BW are similar to those of Fig. 7(a).

IV. CONCLUSION

In summary, we have proposed and experimentally investigated a scheme for generating wideband OFC based on a gain-switched 1550 nm multi-transverse mode VCSEL with dual optical injection (DOI) from two master lasers. For this scheme, the master laser 1 (ML1) and the master laser 2 (ML2) are a tunable semiconductor laser and a distributed feedback (DFB) semiconductor laser, respectively. A 1550 nm multi-transverse mode VCSEL with modulation signal is used to the slave laser (SL), which can simultaneously emit two low-order transverse modes $LP_{01}$ and $LP_{11}$. Under a large signal modulation, the SL can operate at gain-switched state, and two separated sub-combs originated from $LP_{01}$ and $LP_{11}$ modes can be generated. Through further introducing DOI, two expanded sub-combs provided by $LP_{01}$ and $LP_{11}$ modes can link up to form an overall OFC under suitable operating parameters. We take two cases of $P_m = 15.00$ dBm and $P_m = 20.00$ dBm as two examples to discuss the performances of the OFC generated by the gain-switched SL under DOI. The experimental results show that, under a relatively large modulation intensity, a wideband overall OFC about 150.0 GHz formed by two expanded sub-combs of $LP_{01}$ and $LP_{11}$ modes can be achieved by selecting suitable injection parameters. In addition, the effects of the injection wavelength $\lambda_1$ and $\lambda_2$ on the number of comb lines and the BW of the overall OFC are specified. It should be pointed out that the power of the generated comb is relatively weak due to the weak power output of the adopted VCSEL, but the problem may be solved by further introducing a suitable amplifier. Moreover, the amplitude difference among the comb lines may be further decreased by introducing some components such as phase modulator, programmable gain flattening filter, etc. We believe that this proposed scheme of the OFC generation may possess potential applications in polarization sensitive sensing field and polarization division multiplexing optical communications.

REFERENCES

[1] P. D. Lakshmijayasimha, A. K. Anandarajah, E. P. Martin, P. Landais, and P. M. Anandarajah, “Expansion and phase correlation of a wavelength tunable gain-switched optical frequency comb,” Opt. Express, vol. 27, no. 12, pp. 16560–16570, May 2019.

[2] W. Shieh, H. Bao, and Y. Tang, “Coherent optical OFDM: Theory and design,” Opt. Express, vol. 16, no. 2, pp. 841–859, 2008.

[3] D. W. Lin, “An analysis of the performance of ML blind OFDM symbol timing estimation,” IEEE Trans. Signal Process., vol. 66, no. 20, pp. 5324–5337, Oct. 2018.

[4] A. J. Lowery and J. Armstrong, “Orthogonal-frequency-division multiplexing for dispersion compensation of long-haul optical systems,” Opt. Express, vol. 14, no. 6, pp. 2079–2084, 2006.

[5] A. D. Ellis and F. C. G. Gunning, “Spectral density enhancement using coherent WDM,” IEEE Photon. Technol. Lett., vol. 17, no. 2, pp. 504–506, Feb. 2005.

[6] R. Ullah, L. Bo, S. Ullah, M. Yaya, F. Tian, M. K. Khan, and X. Xiangjun, “Flattened optical multicarrier generation technique for optical line terminal side in next generation WDM-PON supporting high data rate transmission,” IEEE Access, vol. 6, pp. 6183–6193, Mar. 2018.

[7] R. Ullah, S. Ullah, A. Ali, M. Yaya, S. Latif, M. K. Khan, and X. Xin, “Optical 1.56 Tbps coherent 4-QAM transmission across 60 km SSMF employing OFC scheme,” AEÜ-Int. J. Electron. Commun., vol. 105, pp. 78–84, Jun. 2019.

[8] T. Yang, C. Shi, L. Wang, X. Chen, H. Pan, H. Chen, M. Zhang, and Z. Zhang, “Fiber nonlinearity and tight filtering impairments mitigation of DP-16QAM Nyquist-WDM systems using multiplexer-free MAP detection,” IEEE Photon. J., vol. 11, no. 6, pp. 1–14, Dec. 2019.

[9] N. R. Newbury, “Searching for applications with a fine-tooth comb,” Nature Photon., vol. 5, no. 4, pp. 186–188, Apr. 2011.

[10] J. Davila-Rodriguez, K. Bagnell, and P. J. Delfyett, “Frequency stability of a 10 GHz optical frequency comb from a semiconductor-based mode-locked laser with an intracavity 10,000 finesse etalon,” Opt. Lett., vol. 38, no. 3, pp. 3665–3667, Sep. 2013.

[11] L. Hou, Y. Huang, and Y. Liu, “Frequency comb with 100 GHz spacing generated by an asymmetric MQW passively mode-locked laser,” Opt. Lett., vol. 45, no. 10, pp. 2760–2763, May 2020.

[12] P. Del’Haye, O. Arcizet, A. Schlösser, R. Holzwarth, and T. J. Kippenberg, “Full stabilization of a microresonator-based optical frequency comb,” Phys. Rev. Lett., vol. 101, no. 5, Jul. 2008, Art. no. 053903.

[13] Z. Xiao, K. Wu, T. Li, and J. Chen, “Deterministic single-soliton generation in a graphene-FP microresonator,” Opt. Express, vol. 28, no. 10, pp. 14933–14947, May 2020.

[14] E. Prior, C. De Dios, A. R. Criado, M. Ortsiefer, P. Meissner, and P. Acedo, “Expansion of VCSEL-based optical frequency combs in the Sub-THz span: Comparison of non-linear techniques,” J. Lightw. Technol., vol. 34, no. 17, pp. 4134–4141, Sep. 1 16.

[15] C. He, S. Pan, R. Guo, Y. Zhao, and M. Pan, “Ultraflat optical frequency comb generated based on cascaded polarization modulators,” Opt. Lett., vol. 37, no. 18, pp. 3834–3836, Sep. 2012.

[16] S. Ullah, R. Ullah, Q. Zhang, H. A. Khalid, K. A. Memon, A. Khan, F. Tian, and X. Xin, “Ultra-wide and flattened optical frequency comb generation based on cascaded phase modulator and LiNbO$_3$-MZM offering Terahertz bandwidth,” IEEE Access, vol. 8, pp. 76692–76699, May 2020.

[17] P. M. Anandarajah, R. Maher, Y. Q. Xu, S. Latkowski, J. O’carroll, S. G. Murdoch, R. Phelan, J. O’Gorman, and L. P. Barry, “Generation of coherent multcarrier signals by gain switching of discrete mode lasers,” IEEE Photon. J., vol. 3, no. 1, pp. 112–112, Feb. 2011.

[18] R. Zhou, T. N. Huynh, V. Vujicic, P. M. Anandarajah, and L. P. Barry, “Phase noise analysis of injected gain switched comb source for coherent communications,” Opt. Express, vol. 22, no. 7, pp. 8120–8125, 2014.

[19] A. Rosado, A. Pérez-Serrano, J. M. G. Tijero, Á. Valle, L. Pesquera, I. Esquivias, “Experimental study of optical frequency comb generation in gain-switched semiconductor lasers,” Opt. Laser Technol., vol. 108, pp. 542–550, Dec. 2018.

[20] A. Rosado, A. Pérez-serrano, J. M. G. Tijero, Á. Valle, L. Pesquera, and I. Esquivias, “Enhanced optical frequency comb generation by pulsed gain-switching of optically injected semiconductor lasers,” Opt. Express, vol. 27, no. 6, pp. 9155–9163, Mar. 2019.

[21] J. Pfeifle, V. Vujicic, R. T. Watts, P. C. Schindler, C. Weimann, R. Zhou, W. Freude, L. P. Barry, and C. Koos, “Flexible terabit/s Nyquist-WDM super-channels using a gain-switched comb source,” Opt. Express, vol. 23, no. 2, pp. 724–738, Jan. 2015.

[22] R. Zhou, S. Latkowski, J. O’Carroll, R. Phelan, L. P. Barry, and P. Anandarajah, “40 nm wavelength tunable gain-switched optical comb source,” Opt. Express, vol. 19, no. 26, pp. B415–B420, Dec. 2011.

[23] M. D. G. Pascual, R. Zhou, F. Smyth, T. Shao, P. M. Anandarajah, and L. Barry, “Dual mode injection locking of a Fabry–Pérot laser for tunable broadband gain switched comb generation,” in Proc. Eur. Conf. Opt. Commun., Valencia, Spain, Sep. 2015, pp. 1–3.

[24] H. Zhu, R. Wang, T. Pu, P. Xiang, J. Zheng, and T. Fang, “A novel approach for generating flat optical frequency comb based on externally injected gain-switching distributed feedback semiconductor laser,” Laser Phys. Lett., vol. 14, no. 2, 2017, Art. no. 026201.
[25] Y. Hong, “Flat broadband chaos in mutually coupled vertical-cavity surface-emitting lasers,” IEEE J. Sel. Topics Quantum Electron., vol. 21, no. 6, Nov. 2015, Art. no. 1801007.

[26] S. Xiang, Y. Zhang, X. Guo, A. Wen, and Y. Hao, “Photonic generation of neuron-like dynamics using VCSELs subject to double polarized optical injection,” J. Lightw. Technol., vol. 36, no. 19, pp. 4227–4233, Oct. 1, 2018.

[27] F. Koyama, “Recent advances of VCSEL photonics,” J. Lightw. Technol., vol. 24, no. 12, pp. 4502–4513, Dec. 2006.

[28] A. R. C. Serrano, C. de Dios Fernandez, E. P. Cano, M. Ortsiefer, P. Meissner, and P. Acedo, “VCSEL-based optical frequency combs: Toward efficient single-device comb generation,” IEEE Photon. Technol. Lett., vol. 25, no. 20, pp. 1981–1984, Oct. 15, 2013.

[29] E. Prior, C. D. Dios, R. Criado, M. Ortsiefer, P. Meissner, and P. Acedo, “Dynamics of dual-polarization VCSEL-based optical frequency combs under optical injection locking,” Opt. Lett., vol. 41, no. 17, pp. 4083–4086, Sep. 2016.

[30] A. Quirce, C. Dios, A. Valle, and P. Acedo, “VCSEL-based optical frequency combs expansion induced by polarized optical injection,” IEEE J. Sel. Topics Quantum Electron., vol. 25, no. 6, Nov. 2019, Art. no. 1500109.

[31] E. P. Cano, C. D. Fernandez, R. C. Serrano, M. Ortsiefer, P. Meissner, and P. Acedo, “Experimental study of VCSEL-based optical frequency comb generators,” IEEE Photon. Technol. Lett., vol. 26, no. 21, pp. 2118–2121, Nov. 1, 2014.

[32] E. Prior, C. De Dios, M. Ortsiefer, P. Meissner, and P. Acedo, “Understanding VCSEL-based gain switching optical frequency combs: Experimental study of polarization dynamics,” J. Lightw. Technol., vol. 33, no. 22, pp. 4572–4579, Nov. 15, 2015.

[33] A. Quirce, C. Dios, A. Valle, L. Pesquera, and P. Acedo, “Polarization dynamics in VCSEL-based gain switching optical frequency combs,” J. Lightw. Technol., vol. 36, no. 10, pp. 1798–1806, May 15, 2018.

[34] G. C. Wilson, D. M. Kuchta, J. D. Walker, and J. S. Smith, “Spatial hole burning and self-focusing in vertical-cavity surface-emitting laser diodes,” Appl. Phys. Lett., vol. 64, no. 5, pp. 542–544, Jan. 1994.

[35] A. Valle, J. Sarma, and K. A. Shor, “Spatial Holeburning Effects on the Dynamics of Vertical Cavity Surface-Emitting Laser Diodes,” IEEE J. Quantum Electron., vol. 31, no. 8, pp. 1423–1431, Aug. 1995.

[36] D. Mahgerefteh, C. Thompson, C. Cole, G. Denoyer, T. Nguyen, I. Lyubomirsky, C. Kocot, and J. Tatum, “Techno-economic comparison of silicon photonics and multimode VCSELs,” J. Lightw. Technol., vol. 34, no. 2, pp. 233–242, Jan. 15, 2016.

[37] J. A. Tatum, D. Gázula, L. A. Graham, J. K. Guenter, R. H. Johnson, J. King, C. Kocot, G. D. Landry, I. Lyubomirsky, A. N. MacInnes, E. M. Shaw, K. Balamarthi, R. Shuhochkin, D. Vaidya, M. Yan, and F. Tang, “VCSEL-based interconnected for current and future data centers,” J. Lightw. Technol., vol. 33, no. 4, pp. 727–732, Feb. 15, 2015.

[38] Y. Su, L. Yu, X. Guo, X. Zhang, J. Liu, and N. Zhu, “Few-mode vertical-cavity surface-emitting lasers for space-division multiplexing,” J. Semi-cond., vol. 38, no. 9, Sep. 2017, Art. no. 094002.

[39] A. Rosado, A. Pérez-Serrano, J. M. G. Tijero, A. V. Gutierrez, L. Pesquera, and I. Esquivias, “Numerical and experimental analysis of optical frequency comb generation in gain-switched semiconductor lasers,” IEEE J. Quantum Electron., vol. 55, no. 6, Dec. 2019, Art. no. 2001012.

**Guang-Qiong Xia** was born in Fushun, China, in 1970. She received the B.Sc., M.Sc., and Ph.D. degrees in optics from Sichuan University, Chengdu, China, in 1992, 1995, and 2002, respectively. She is currently a Full Professor with the School of Physics, Southwest University, Chongqing, China. She has authored or coauthored over 140 publications, including about 100 journal articles. Her current research interests include the nonlinear dynamics of semiconductor lasers, the synchronization and control of chaotic semiconductor lasers, and optical secure communication based on semiconductor lasers, and microwave photonics.

**Zai-Fu Jiang** was born in Jingmen, China, in 1981. He received the M.Sc. degree in theoretical physics from Chongqing University, Chongqing, China, in 2007. He is currently pursuing the Ph.D. degree in optics with Southwest University. His main research interest includes the nonlinear dynamics of quantum dot lasers.

**Tao Deng** was born in Sichuan, China, in 1982. He received the B.Sc. degree in electronic information engineering and the M.Sc. degree in optics from Southwest University, Chongqing, China, in 2002 and 2005, respectively, and the Ph.D. degree in optics from Sichuan University, Chengdu, China, in 2012. He is currently a Full Professor with the School of Physics, Southwest University. He has authored or coauthored over 30 publications.

**Xiao-Dong Lin** was born in Chongqing, China, in 1975. He received the B.Sc., M.Sc., and Ph.D. degrees in optics from Sichuan University, Chengdu, China, in 1998, 2002, and 2012, respectively. His current research interests include the nonlinear dynamics of semiconductor lasers and microwave photonics.

**Wen-Yan Yang** was born in Chifeng, China, in 1978. She received the M.Sc. degree in optics and the Ph.D. degree in applied mathematics from Southwest University, Chongqing, China, in 2005 and 2020, respectively. Her current research interest includes the nonlinear dynamics of semiconductor lasers.

**Yan-Hong Jin** was born in Handan, China, in 1983. She received the M.Sc. degree in applied mathematics from Chongqing Normal University, Chongqing, China, in 2011. She is currently pursuing the Ph.D. degree in applied mathematics with Southwest University. Her research interest includes microwave photonics.
ZHEN-ZHEN XIAO was born in Jingzhou, China, in 1992. She received the M.Eng. degree in information and communication engineering from Wuyi University, Jiangmen, China, in 2019. She is currently pursuing the Ph.D. degree in optics with Southwest University. Her research interests include the applications of lidars.

DIAN-ZUO YUE was born in Hebei, China, in 1982. He received the M.Sc. degree in information processing and automation from the Inner Mongolia University of Science and Technology, Baotou, China, in 2014. He is currently pursuing the Ph.D. degree in optics with Southwest University. His current research interests include the optoelectronic and all-optical reservoir computing and its applications.

CHUN-XIA HU was born in Zhoukou, China, in 1982. She received the M.Sc. degree in optics from Southwest University, Chongqing, China, in 2008, where she is currently pursuing the Ph.D. degree in optics. Her research interests include the nonlinear dynamics of semiconductor lasers and optical chaotic secure communication.

BING CUI was born in Dengzhou, China, in 1984. He received the M.Sc. degree in applied mathematics from Northwest A & F University, Xianyang, China, in 2012. He is currently pursuing the Ph.D. degree in optics with Southwest University. His research interest includes the nonlinear dynamics of semiconductor lasers.

MIN DAI was born in Dafang, China, in 1975. She received the M.Sc. degree in optics from the University of Shanghai for Science and Technology, Shanghai, China, in 2011. She is currently pursuing the Ph.D. degree with Southwest University. Her research interest includes the nonlinear dynamics of high-power lasers.

ZHENG-MAO WU was born in Wuyuan, China, in 1970. He received the B.Sc., M.Sc., and Ph.D. degrees in optics from Sichuan University, Chengdu, China, in 1992, 1995, and 2003, respectively. He is currently a Full Professor with the School of Physics, Southwest University, Chongqing, China. He has authored or coauthored over 100 publications. His current research interests include the nonlinear dynamics of semiconductor lasers and their applications, and chaotic semiconductor lasers and their applications.