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Optical comb generator with flat-topped spectral response using one electroabsorption-modulated laser and one phase modulator

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Abstract. We experimentally demonstrated a novel structure for generating an optical frequency comb source for multicarrier modulation in an optical transmission system. In the proposed scheme, the integration of an electroabsorption-modulated laser cascaded with a phase modulator is employed, both of which are driven and synchronized via a common sinusoidal radio frequency signal. The optimal operating range defined as a spectral flatness with less than 3-dB power fluctuation can be obtained through numerical simulation. Using the proposed scheme, we can achieve 10 flat-topped and frequency-locked optical carriers with a 12.5-GHz frequency spacing. On–off-keying intensity-modulated signals with 3.125 and 12.5 Gb/s are transmitted error-free over 20 km standard single-mode fiber utilizing the proposed optical frequency comb source for an optical wavelength-division multiplexing transmission system. © *2020 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.59.1.016112]

Keywords: phase modulator; electroabsorption modulator; intensity modulation and direct detection; optical frequency comb source.

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1 Introduction

An efficient structure of multicarrier optical signal source has been extensively investigated for various optical communication systems, including wavelength-division multiplexing (WDM) source,[1–3] optical signal processing,[4,5] reconfigurable optical pulse generator,[6] and other non-telecom areas.[7–9] Recently, many technical approaches have been proposed to generate optical frequency combs. Among them, a commonly known method that employs a single continuous-wave (CW) narrow-linewidth laser source modulated by a single external optical modulator, such as an in-phase/quadrate modulator[10,11] or a polarization modulator,[12] is widely adopted to generate a narrow-linewidth multicarrier source. In addition, a CW pump laser interacting with a microresonator can also be used to generate optical frequency combs.[13–15] However, the performance of spectral flatness of the combs generated by these two aforementioned methods is unsatisfactory. By cascading multiple modulators [i.e., an intensity modulator (IM) cascaded with a phase modulator (PM)[16–18] or cascaded with PMs[19]] with a CW laser, the flatness of the generated optical combs could be improved at the expense of a more complicated system structure that requires an additional costly CW laser source. A directly modulated distributed feedback (DFB) laser, which concurrently acts as a laser source and an optical signal modulator, cascaded with a PM can be used for optical frequency comb generation as a simplified structure, thus eliminating the requirement of one external modulator.[20,21] However, a directly modulated laser (DML) exhibits large chirp, low-frequency response, and low extinction ratio, which limits optical transmission data rate and distance. In addition, the scheme of Ref. 21 in which the PM is driven by different radio frequency (RF) clocks needs an extra frequency multiplier.

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This increases the system complexity and induces more insertion loss. Therefore, it is important to seek a comprehensive solution for optical frequency comb generator.

Recently, a commercially available electroabsorption-modulated laser (EML) consisting of a semiconductor laser with an electroabsorption modulator (EAM)[22] has been widely employed in optical communications. In contrast to DML, EML has smaller chromatic dispersion and thus can be used in high-speed and long-distance transmission systems. A flat-topped optical frequency comb generator using one EAM and two cascaded PMs has been demonstrated for optical waveform generation.[23] However, the system structure in Ref. 23 is relatively complex, requiring two PMs, a 3-nm optical filter, polarization controllers, and multiple phase shifters (PSs). These extra devices greatly increase the system insertion loss and inevitably cause oscillation that affects the stability of the generated optical multicarrier.

In this paper, we demonstrated a simplified optical multicarrier generator with improved flatness in spectral response by employing a single EML cascaded with one PM. Compared with the reported scheme,[23,24] extra devices are eliminated, which effectively reduces the complexity and cost of the system. More importantly, we achieved a satisfactory flatness of less than 3 dB. We numerically analyzed the comb generation scheme to optimize the reverse bias voltage of an EML and the driving voltage of an EML and a PM. Ten frequency-locked subcarriers are generated and experimentally demonstrated based on our proposed scheme. The frequency spacing of the generated optical frequency comb is 12.5 GHz, and the spectral flatness is maintained at <3 dB. Utilizing the generated comb source, error-free transmission of 3.125 and 12.5 Gb/s on–off-keying (OOK) data over 20 km standard single-mode fiber (SSMF) is achieved. The proposed optical multicarrier signal source can be applied to high-speed optical dense WDM transmission systems.

2 Experimental Analysis and Numerical Simulation

2.1 *Experimental Analysis*

It has been reported that flat-topped optical frequency comb generation can be realized when a flat-top pulse train is modulated by an ideal periodic parabolic temporal phase signal.[16] A convenient approach for flat-top pulse train generation is to employ one narrow-linewidth CW laser modulated by one IM driven by a sinusoidal RF signal. However, it is difficult to generate a perfect parabolic temporal phase. A sinusoidal temporal phase signal, which can be generated by a PM driven by the RF signal, is often utilized as an approximation of parabolic temporal phase. Thus, flat-topped optical frequency comb generation can be achieved by the combination of a PM and a cascaded IM directly. As we know, however, the series expansion of the sinusoidal function has undesirable higher-order terms other than the quadratic term. Thus, the sinusoidal temporal phase apart from its peak or valley has a considerable difference from the ideal parabolic temporal phase, which causes the degradation of the achieved spectral flatness, particularly for those outer subcarriers. It has been proved that the nonlinear effect of the IM can shorten the output pulse and weaken the higher-order terms of the sinusoidal function.[17] Thereby, the generated waveform can be more similar to the parabolic temporal phase, and the spectral flatness can be improved.

There are mainly two types of IMs: one is based on the linear electro-optic effect and the other is based on the electroabsorption effect. Compared with the electro-optic IM, the EAM has many advantages, such as small size, low price, and easy integration. In particular, the EAM can be integrated with a semiconductor laser to form an EML, which can effectively reduce the interface losses and is commercially available. Owing to the strong nonlinear electroabsorption effect, the EAM can generate a much shorter optical pulse compared with the electro-optic IM.[23] Thus, cascaded EAM and PM can be much closer to the theoretical model of the parabolic phase modulation of the flat-top pulse train. When we arrange only one PM to modulate the CW light wave at a center frequency of f_c, the PM output optical field is given as

$$E_{\mathrm{out1}}(t) = E_0 \exp(j2\pi f_c t) \exp[jR \sin(2\pi f_s t)] = E_0 \sum_{n=-\infty}^{\infty} J_n(R) \exp[j2\pi(f_c + n f_s)t], \quad (1)$$

where E_0 represents the amplitude of the electrical field, f_s expresses the frequency of RF driving signal, f_c is the center frequency of wavelength, J_n denotes the first kind of Bessel function, and R expresses the PM modulation index. Figure 1(a) corresponds to the scenario when the cascaded PM and EML are used to generate the comb source, and the output optical intensity is expressed as

$$\begin{aligned} E_{\text{out2}}(t) &\approx E_0[1 + R_1 \sin(2\pi f_s t)] \exp(j2\pi f_c t) \exp[jR_2 \sin(2\pi f_s t)] \\ &= E_0 \sum_{n=-\infty}^{\infty} J_n(R_2) \exp\{j2\pi[f_c + (n-1)f_s]t\} \\ &\quad - jE_0 \frac{R1}{2} \sum_{n=-\infty}^{\infty} J_n(R_2) \exp\{j2\pi[f_c + (n+1)f_s]t\} \\ &\quad + jE_0 \frac{R_1}{2} \sum_{n=-\infty}^{\infty} J_n(R_2) \exp\{j2\pi[f_c + (n-1)f_s]t\}, \end{aligned} \tag{2}$$

where R_1 is the EML modulation index and R_2 is the PM modulation index. Compared with Eq. (1), the second and third terms in the right side of Eq. (2) can flatten the amplitude of the generated optical multicarrier and bring in a new spectrum element. With proper reverse bias voltage and RF-driving voltage, flat-topped optical frequency combs can be achieved. Moreover, by increasing the RF-driving voltage applied on the cascaded PM, more optical carriers can be achieved.

According to the aforementioned analysis, we propose an optical frequency comb source employing an EML as well as a cascaded PM, as shown in Fig. 1(a). In this system, an EAM is the typical model; Fig. 1(b) shows the output optical power changing with bias voltage for the EAM. In the following section, we will demonstrate both simulation and experiment discussions; it is concluded that our proposed optical frequency comb source generation with a good spectral flatness can be realized when the RF-driving voltage of both the EML and PM and the reverse bias voltage of the EML are optimized.

2.2 *Numerical Simulation*

We use VPI software to simulate the proposed system. Since there is no EML model in VPI software, a DFB laser model and an EAM model are cascaded together instead of the EML. In this process, we set the driving frequency as 12.5 GHz, and time window and sampling rate are fixed as 16 ns and 1024 GHz, respectively. By adjusting the reverse direct current (DC) bias voltage on the EML and the voltage amplitude of RF driving on EML and PM, we can obtain the best working zones for the system.

To improve the spectral flatness, three different EML bias voltages of −1, −1.5, and −2 V are selected for testing to utilize the nonlinear electroabsorption effect of the EAM effectively. Considering these three cases, we can discuss the number and spectral flatness variation of the generated multicarrier with the driving voltage, the result of which can be observed in Fig. 2. When the driving voltage of the EML is 0 V, the EML does not work, which means that only one PM can be utilized to generate the optical frequency comb. In this case, the flatness of the

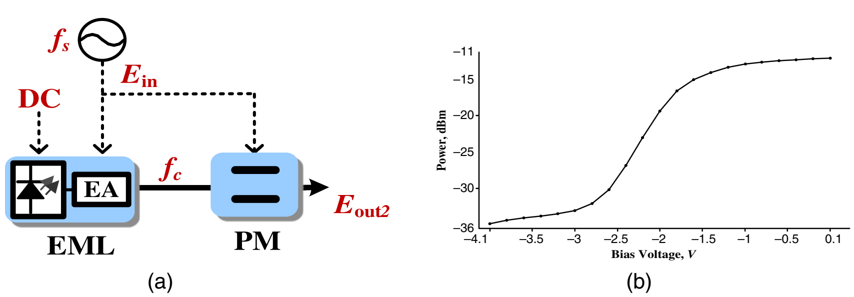

Fig. 1 (a) Structure of the cascaded EML and PM in the optical comb generation system. (b) Output optical power changing with bias voltage for EAM.

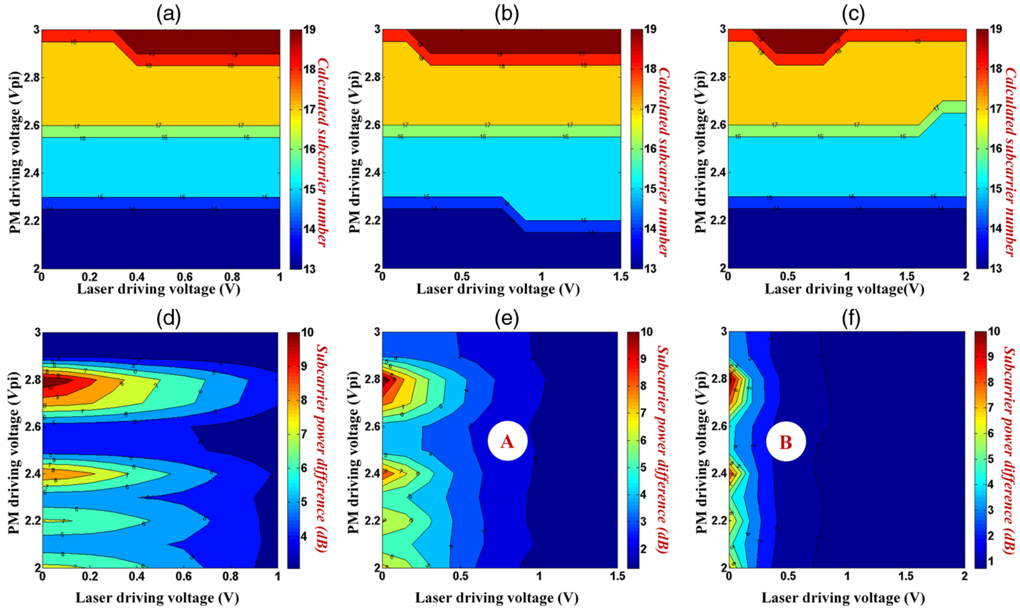

Fig. 2 Calculated multicarrier number versus RF-driving voltage when EML bias is (a) −1 V, (b) −1.5 V, and (c) −2 V. Multicarrier spectral flatness versus RF-driving voltage when EML bias is (d) −1 V, (e) −1.5 V, and (f) −2 V.

generated multicarrier is very poor. When increasing the driving voltage of the EML, the flatness of the comb spectrum can be effectively improved, while the number of multicarrier signals increases with the increasing of the PM-driving voltage. We define the working range with a spectral flatness of less than 3 dB as the optimum working zones. Based on the simulation results, it can be concluded that the optimum working zones are A and B in Figs. 2(e) and 2(f). The driving voltage amplitudes of the EML for zones A and B are set above 0.7 V and over 0.25 V, respectively. In these regions, 13 or more carriers can be generated with a flatness of less than 3 dB in our proposed system. Moreover, by increasing the reverse bias voltage of the EML within the nonlinear operating range, the optimal operating area of the system can be increased.

Figures 3(a) and 3(b) depict the optical spectrum for the tEML and PM, respectively, when the driving voltage the for PM is set to 2.4 V_{pi} and the reverse bias voltage and driving voltage for the EML are −1.5 and 1.5 V, respectively. At this point, we can generate 15 multicarriers with a spectral flatness below 3 dB.

3 Experimental Setup and Results

3.1 *Experimental Setup*

Figure 4 depicts our experimental setup of optical frequency comb generation and intensity modulation and direct detection (IM–DD) transmission using the EML and PM. First, a

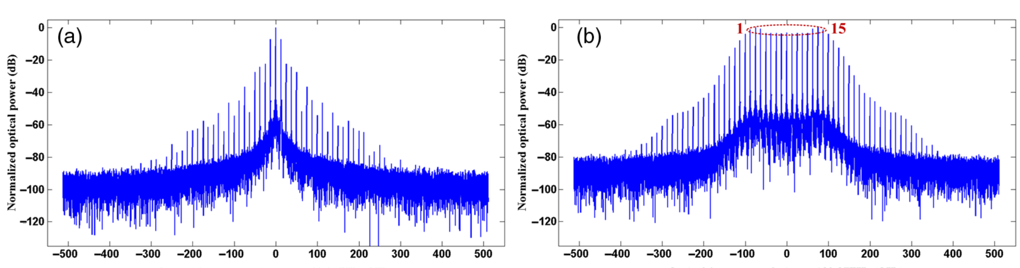

Fig. 3 Optical spectrum from (a) EML and (b) PM, when the reverse bias voltage and driving voltage for EML are set to −1.5 and 1.5 V and the driving voltage for PM is set to 2.4 V_{pi}.

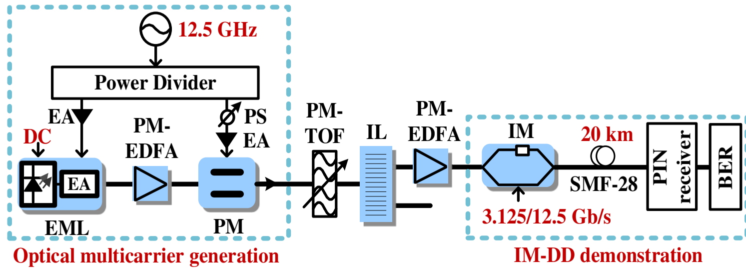

Fig. 4 Experimental setup of the proposed optical frequency comb generator for OOK signal transmission.

sinusoidal RF signal of 12.5 GHz is divided into two equal branches: one of them is amplified to 24 dBm for EML driving and the other one is boosted to 30 dBm for PM driving. Before the PM, a PS is needed to synchronize the two RF signals. Then, to handle the issue between the EML and the PM to compensate for the modulation losses, a polarization-maintaining erbium-doped fiber amplifier (PM-EDFA) is arranged.

Figure 5(a) illustrates the output power changing with the DC bias of the DFB laser without the DC bias and driving voltage of the EAM. Figure 5(b) gives the output power changing with reverse DC bias of the EAM when the DC bias voltage of the DFB is set to 33 mA. The saturation output power of the EAM is around −14 dBm. The commercially available EML is constructed by an EAM and a DFB source. Its linewidth is around 1.9 MHz (this value is offered by the manufacturer), and it can be affected in practice by the DC bias applied on the EAM. And the output spectrum of EML is depicted in Fig. 5(c), when the driving signal of the EAM is 1.98 V and the reverse bias is −1 V. Note that the average output power of the DML, which can reach 10 dBm, is very high. In contrast, EML has a big insertion loss under the high reverse DC bias, so the average output power of the EML is less than −10 dBm. The EAM insertion loss is around 10 dB if the reverse DC bias is set at −1 V. With 50 ohms input resistance of the PM, the RF-driving voltage at the frequency of 12.5 GHz is around 10 V and the PM half-wave voltage is 4.2 V, so the calculated PM modulation index is 2.4. Figure 5(d) illustrates the output spectrum of the system when only the PM has an RF-driving signal of 12.5 GHz. We can see that the flatness of the 10 carriers generated in the figure is very poor at around 9 dB. In contrast, in this system where both the EML and the PM have a driving RF signal of 12.5 GHz, as shown in Fig. 5(e), the output spectrum has a much better flatness of less than 3 dB. The frequency spacing of the 10 generated carriers is 12.5 GHz. This result effectively proves that it is feasible to

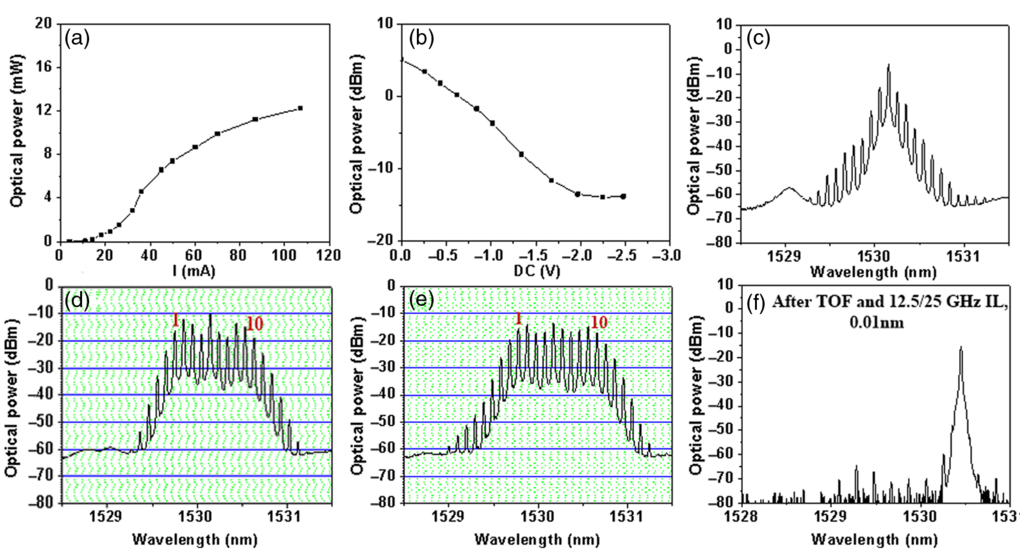

Fig. 5 Output optical power changing with input DC bias of (a) DFB laser and (b) EAM. Optical spectrum is shown for (c) EML, (d) only PM, (e) both EML and PM, and (f) PM-TOF.

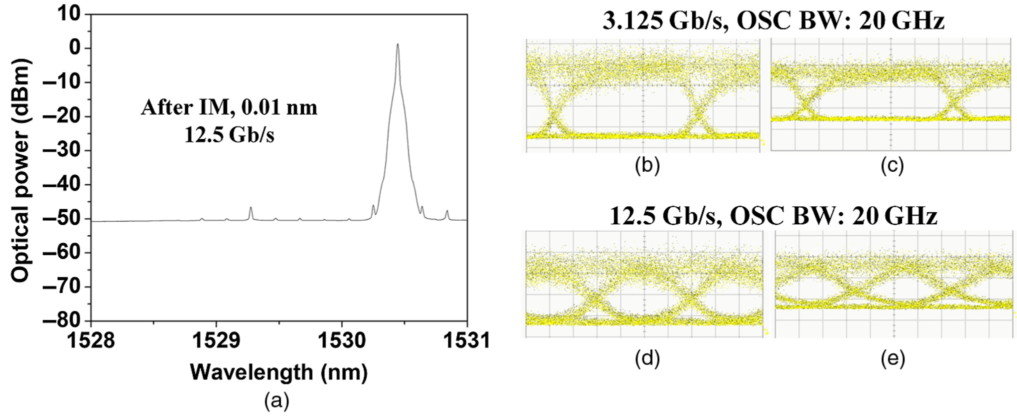

Fig. 6 (a) Spectrum after the IM; (b) and (c) eye diagrams of observed 3.125 Gb/s signal before and after SSMF delivery; (d) and (e) eye diagrams of observed 12.5 Gb/s signal before and after SSMF delivery.

generate a flattened optical frequency comb employing a combination of an EAM and a PM in our proposed system.

To mitigate the amplified spontaneous emission noise caused by PM-EDFA, a polarization-maintaining tunable optical filter (PM-TOF) is placed after the cascading system of the EM and PM. Then an interleaver (IL), along with that aforementioned PM-TOF with an adjustable bandwidth ranging from 0.1 to 9 nm, is used to select the optical carrier we need. Figure 5(f) is the spectrum of the optical carrier after 12.5/25 GHz IL selection with a bandwidth of 0.1 nm. After that, another PM-EDFA is used. The selected carrier is then modulated by an electrical binary signal using an IM. This electrical binary signal is 12.5 and 3.125 Gb/s is generated from a pulse pattern generator with a pseudo-random binary sequence length of 2^{23}-1, respectively. After 20 km of SSMF transmission, a positive intrinsic-negative (PIN) receiver with a 3-dB bandwidth of 7.5 GHz can be used to directly detect the optical signal. The launched power is 4 dBm.

3.2 *Experimental Results*

Figure 6(a) illustrates the spectrum after IM. Figures 6(b) and 6(c) are eye diagrams of the observed 3.125 Gb/s signal before and after the 20-km SSMF delivery, respectively. Similarly, Figs. 6(d) and 6(e) are the observed 12.5 Gb/s transmission. These eye diagrams are more or less asymmetric because of the nonlinear effect caused by EML. The extinction ratio can reach over 10 dB when signals are not transmitted. After SSMF transmission, the signals are directly received without EDFA and suffer large power penalty, degrading eye diagram performance, as shown in Figs. 6(c) and 6(e).

Figures 7(a) and 7(b) depict the bit error rate (BER) performance for 3.125 and 12.5 Gb/s signal transmission versus the optical power in the PIN receiver, respectively. The optical power

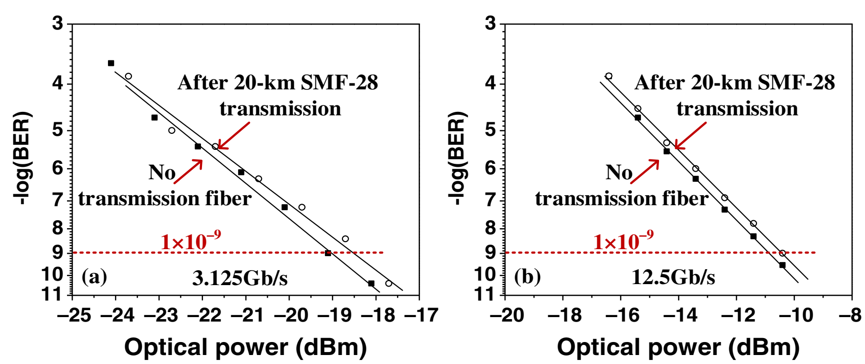

Fig. 7 BER changing with optical power in PIN receiver when the data rate is (a) 3.125 Gb/s and (b) 12.5 Gb/s.

penalty for both signals is 0.5 dB at 1×10^{-9} BER over the 20-km SSMF delivery. At the BER of 1×10^{-9}, the power requirement for 12.5 Gb/s delivery is about 8 dB larger compared with the 3.125 Gb/s transmission case. But the power difference is theoretically simulated as 6 dB. The reason for this phenomenon is that the PIN receiver is suitable for 10 Gb/s bit rate detection of which the 3-dB bandwidth is 7.5 GHz in our proposed system, so the extra penalty (about 2 dB) is caused when the data rate increases to 12.5 Gb/s. Experimental measurements of the other generated carriers are also implemented, and they have a similar performance. This proves that our proposed scheme of the cascaded EML and PM is feasible for IM–DD-based fiber-optic transmission.

4 Conclusions

We experimentally demonstrated a simple and novel signal generator structure that employs an EML cascaded with a PM to generate an optical frequency comb source for multicarrier modulation in optical transmission systems. In our scheme, both the EML and the PM are driven by a synchronous sinusoidal RF signal. We theoretically analyzed the operation principle of multicarrier generation and obtained optimal operating zones through the numerical simulation. Using the proposed scheme, we experimentally generated 10 frequency-locked carriers with 12.5-GHz frequency spacing and less than 3 dB spectral flatness. Utilizing the generated optical frequency comb source, the error-free transmission of OOK signals at 3.125 and 12.5 Gb/s over the 20-km SSMF has been realized based on IM–DD. Thus, our proposed optical frequency comb source with a narrow frequency spacing can be applied to high-speed dense-WDM optical transmission systems.

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