

Article

Broadened and Flattened Optical Frequency Comb Based on Directly Modulated DFB Semiconductor Laser

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Abstract

A simple scheme for generating a broadened and flattened optical frequency comb (OFC) based on a directly modulated distributed feedback (DFB) semiconductor laser cascaded with electro-optic modulators is proposed. The initial OFC is generated by a gain-switched DFB semiconductor laser. The number of comb lines is further expanded by cascading a phase modulator and the flatness performance is optimized by adjusting the power of the radio frequency (RF) and bias voltage of the cascaded Mach–Zehnder modulator. Moreover, the spacing of comb lines can be flexibly tuned by varying the frequency of the RF signal, and an OFC with seven spectral lines within a 4.72 dB power variation is demonstrated. The 17-line OFC with a frequency spacing of 12.5 GHz and a flatness of 3 dB is further applied to an optical transmission system, which enables error-free transmission of a non-return-to-zero data signal. The proposed scheme is expected to find applications in flexible-grid optical transmission systems.

Keywords: optical frequency comb; distributed feedback semiconductor laser; gain-switching; electro-optic modulator

1. Introduction

Optical frequency comb (OFC) is a spectrum composed of a set of discrete equally spaced lines [1], and it is widely applied in microwave photonic signal processing [2,3], optical communication [4,5], arbitrary waveform generation [6], precision ranging [7] and spectral measurement [8]. Generally, a larger number of comb lines, lower flatness, wider tunable range of frequency spacing, and higher side-mode suppression ratio indicate superior OFC performance. Many approaches have been proposed to generate OFC, such as mode-locked lasers (MLLs) [9,10], recirculating frequency shifters (RFSs) [11,12], Kerr microresonators [13–15], nonlinear effects [16,17], directly modulated lasers [18] and external modulators [19,20]. MLL-based OFC generation utilizes mode-locking technology and Fourier transform to produce OFC, which can achieve large bandwidths. However, stable mode-locking is hard to sustain, and the tuning range of the central wavelength and frequency spacing is limited [21]. RFS-based loops offer high flexibility, but suffer from significant noise accumulation over multiple round trips, resulting in poor phase



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stability and flatness [22]. The OFC generated by Kerr microresonator exhibits excellent coherence, but the energy conversion efficiency is low [23]. Nonlinear-effect-based methods, such as stimulated Brillouin scattering, can also generate OFC, but their tunability is constrained by the self-lasing effect of erbium-doped fibers in the cavity [24]. The method of generating OFC based on external modulators has become a research hotspot due to its simple structure and tunable frequency spacing, mainly including electro-optic modulators, electro-absorption modulators, acousto-optic modulators, and magneto-optic modulators. In the research of generating OFC based on electro-optic modulators, the Mach–Zehnder modulator (MZM), dual-parallel MZM (DPMZM), dual-drive MZM, phase modulator (PM), intensity modulator, and polarization modulator have been widely used. Electro-optic frequency comb generation typically employs a continuous-wave (CW) laser as the initial optical source, where the output spectrum is only a single-frequency optical carrier. Therefore, an electro-optic modulator driven by an external radio frequency (RF) signal is usually required after the CW laser to generate the initial OFC [25]. This inevitably increases the complexity, cost, and insertion loss of the initial OFC generation, and the resulting flatness and the number of lines typically involve complex bias point control [26]. The directly modulated distributed feedback (DFB) semiconductor laser is one of the simplest methods for OFC generation, which requires no additional electro-optic modulator and utilizes the gain-switching effect to generate the initial OFC, significantly reducing system complexity and cost while maintaining good frequency spacing tunability [27]. Due to the inherent modulation bandwidth limitations of the laser, the resulting OFC has a limited number of comb lines and poor flatness [28]. Although directly modulated DFB semiconductor lasers under optical injection can optimize the OFC's performance, they require an additional light source and complex injection control, resulting in a relatively complex system architecture [29]. Moreover, to further improve OFC's performance, cascading electro-optic modulators has become a common approach. For example, a flat OFC based on cascading three PMs from a CW laser has been demonstrated, achieving 21 comb lines with a flatness within 3 dB, but at the cost of high expenses due to the use of multiple PMs [30]. Additionally, some researchers have employed a harmonic-based DPMZM and PM cascade architecture to generate a 13-line OFC with a flatness within 1 dB, also using a CW laser as the initial optical source, achieving excellent flatness performance but with a relatively small number of comb lines [31].

In this paper, a novel and simple scheme based on the gain-switched laser cascaded with optical modulators is proposed to obtain an OFC with higher spectral flatness and more comb lines. The initial OFC is generated by modulating the DFB semiconductor laser with the RF signal benefitting from the gain-switching effect. Then, the number of comb lines of the initial OFC is increased by PM and the flatness performance is improved by MZM. The proposed scheme features a simple structure, low cost, and flexible tunability. Moreover, the OFC generated by this scheme is applied as a multi-carrier optical source in an optical transmission system, where the transmission performance of the non-return-to-zero (NRZ) data signal is systematically investigated within a flexible-grid optical communication framework.

2. Theoretical Analysis

Figure 1 shows the schematic diagram of the proposed approach for optimizing the OFC generated by a directly modulated DFB semiconductor laser cascaded with electro-optic modulators. Based on the gain-switching effect, an initial OFC is generated by directly modulating the DFB semiconductor laser with RF1. This initial optical signal is then injected into the PM. By adjusting the phase shifter (PS) and the gain of the electrical amplifier (EA), the number of comb lines can be increased. Finally, the OFC optimized by the PM is used

as the input optical carrier signal for the MZM. By adjusting the power of RF2 and the bias voltage applied to the MZM, the flatness performance can be further optimized to obtain an ideal OFC. The polarization controllers (PCs) are used to align the polarization state of the optical carrier with that of the modulator to achieve maximum output power.

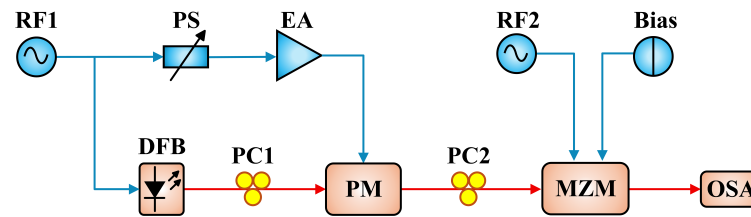


Figure 1. Optimized design of OFC by directly modulated DFB semiconductor laser based on cascaded electro-optic modulators. RF: radio frequency signal; DFB: distributed feedback semiconductor laser; PS: phase shifter; EA: electrical amplifier; PC: polarization controller; PM: phase modulator; MZM: Mach–Zehnder modulator; OSA: optical spectral analyzer.

DFB semiconductor lasers can generate OFC based on the gain-switching effect. The core mechanism relies on ensuring that photons within the cavity are not completely depleted when the laser is modulated by alternating half-cycles of a sine wave, thereby successfully generating OFC. Specifically, the modulation mechanism involves directly modulating the laser by applying a large-amplitude sinusoidal current, causing the carrier density to oscillate periodically above and below the threshold level. This periodic “on–off” switching effect ultimately generates a sequence of discrete short optical pulses. By setting the modulation frequency to a value greater than or equal to the laser’s relaxation oscillation frequency (ROF), each current pulse builds up from the decaying tail of the preceding pulse, which reduces temporal jitter and thus enhances the pulse-to-pulse coherence, thereby generating an OFC [32]. The initial OFC generated by the gain-switching effect can be analyzed based on the following single-mode rate equations for semiconductor lasers [33]:

$$\frac{dE}{dt} = \frac{1}{2} \left(\frac{\gamma v_g a_0 (N - N_0)}{1 + \xi E^2} - \frac{1}{\tau_p} \right) E + \frac{\gamma \beta N}{2E\tau_n} \quad (1)$$

$$\frac{dN}{dt} = \frac{I_b + I_m \cos(2\pi f_m t)}{eV} - \frac{v_g a_0 (N - N_0) E^2}{1 + \xi E^2} - \frac{N}{\tau_n} \quad (2)$$

$$\frac{d\theta}{dt} = \frac{\alpha}{2} \left(\frac{\gamma v_g a_0 (N - N_0)}{1 + \xi E^2} - \frac{1}{\tau_p} \right) \quad (3)$$

The above laser rate equations show the relationship among the slowly varying amplitude E , the carrier density N and the phase θ of the optical field. All parameters have unique meanings. Some relevant parameter settings of the DFB semiconductor laser in this work are shown in Table 1:

Neglecting the phase difference between pulses, the optical signal $E_{in}(t)$ generated by DFB semiconductor laser, which is directly modulated by the RF1 $V(t) = V_{RF,PM} \sin(\omega_{RF,PM} t + \varphi_{RF,PM})$ under the gain-switching effect, can be approximately written as follows [34]:

$$E_{in}(t) = \sum_n p(t - nT) = p(t) \otimes \sum_n \delta(t - nT) \quad (4)$$

where p is the shape of an individual pulse, δ is the Dirac delta function and n is an integer representing the pulse number.

Table 1. Some parameter defines and values.

Parameter	Value
Confinement factor (γ)	0.3
Group velocity (v_g)	$7.5 \times 10^7 \text{ m s}^{-1}$
Linear material gain coefficient (a_0)	$3.3 \times 10^{-20} \text{ m}^2$
Carrier density at transparency (N_0)	$1.5 \times 10^{24} \text{ m}^{-3}$
Nonlinear gain compact factor (ξ)	$3 \times 10^{-23} \text{ m}^3$
Photon lifetime (τ_p)	$3 \times 10^{-12} \text{ s}$
Carrier lifetime at threshold (τ_n)	$2.1 \times 10^{-9} \text{ s}$
Spontaneous emission rate (β)	1×10^{-4}
Bias current (I_b)	0.05 A
Cosine signal current (I_m)	0.2 A
Electron charge (e)	$1.6 \times 10^{-19} \text{ C}$
Volume of the active region (V)	$1.8 \times 10^{-16} \text{ m}^3$
Linewidth enhancement factor (α)	4

The above signal is input into the PM as the initial optical carriers. The RF1 is processed by PS and EA and then used as an electrical modulation signal to drive the PM. PS can optimize the phase of the applied modulation signal. Neglecting the initial phase of the electric field, the output optical signal via PM can be expressed as follows:

$$\begin{aligned}
 E_{PM}(t) &= E_{in}(t) \sum_k J_k(m_{PM}) \exp(jk\omega_{RF,PM}t + jk\varphi_{RF,PM}) \\
 &= \sum_n \left[\sum_k J_k(m_{PM}) \exp \left(\begin{matrix} jk\omega_{RF,PM}t \\ +jk\varphi_{RF,PM} \end{matrix} \right) \right] p(t - nT)
 \end{aligned} \quad (5)$$

where m_{PM} is the modulation index of PM, $m_{PM} = \pi V_{RF,PM}/V_\pi$, V_π is the half-wave voltage of PM and $J_k(m_{PM})$ is the k -th order Bessel function of the first kind.

As shown in Equation (5), it can be seen that after PM modulation, for each original comb line generated by the gain-switched DFB semiconductor laser, multiple optical sidebands with a spacing of $\omega_{RF,PM}$ will be produced around it, and their amplitudes are related to $J_k(m_{PM})$. Therefore, when the same external RF signal is applied to both the DFB semiconductor laser and PM, spectral broadening can be optimized by adjusting the PS and the gain of the EA.

Taking the optical signal $E_{PM}(t)$ output from the PM as the input optical carrier signal of the MZM, when $E_{PM}(t)$ reaches the left Y-branch, it is equally divided into two parallel waveguide branches. Here, the optical signals of two branches can be expressed as follows:

$$E_1(t) = E_2(t) = \frac{E_{PM}(t)}{\sqrt{2}} \quad (6)$$

The external drive signal applied to the upper and lower optical waveguides of MZM includes the RF2 and bias voltage, which can be expressed as follows:

$$\begin{cases} V_1(t) = V_{RF1} \sin(\omega_{RF1}t + \varphi_{RF1}) + V_{DC1} \\ V_2(t) = V_{RF2} \sin(\omega_{RF2}t + \varphi_{RF2}) + V_{DC2} \end{cases} \quad (7)$$

Generally, the initial phases of the RF signal for the two branches differ solely in terms of φ_{RF} , while other parameters remain identical. Meanwhile, the phase changes caused by bias voltage V_{DC1} and V_{DC2} are defined as ϕ_1 and ϕ_2 , respectively. $\phi_i = \pi V_{DCi}/V_{\pi,MZM}$, ($i = 1, 2$), where $V_{\pi,MZM}$ is the half-wave voltage of MZM. The two

optical signals are then coupled in the right Y-branch, and the MZM output signal $E_{MZM}(t)$ can be expressed as follows:

$$E_{PM}(t) = \frac{E_{PM}(t)}{2} \exp(jl\omega_{RF,MZM}t) \sum_l J_l(m_{MZM}) \left[\begin{array}{c} \exp(jl\varphi_{RF1} + j\phi_1) \\ + \exp(jl\varphi_{RF2} + j\phi_2) \end{array} \right] \quad (8)$$

$$= \frac{1}{2} \sum_n \left\{ \begin{array}{c} \sum_k \sum_l [J_k(m_{PM}) J_l(m_{MZM})] \\ \cdot \exp[jt(l\omega_{RF,MZM} + k\omega_{RF,PM}) + jk\varphi_{RF,PM}] \\ \cdot [\exp(jl\varphi_{RF1} + j\phi_1) + \exp(jl\varphi_{RF2} + j\phi_2)] \end{array} \right\} p(t - nT)$$

where m_{MZM} is the modulation index of MZM, $m_{MZM} = \pi V_{RF,MZM} / V_{\pi,MZM}$, and $J_l(m_{MZM})$ is the l -th order Bessel function of the first kind.

As shown in Equation (8), when the RF1 frequency of the PM and DFB semiconductor laser is equal to or in an integer multiple relationship with the RF2 frequency of the MZM, by adjusting the amplitude of RF2 and the applied bias voltage, the MZM can be brought to a proper operating point; i.e., by adjusting the modulation index of the MZM and the phase shift caused by the bias voltage, the required optical sidebands can be obtained, which can further optimize the flatness of the OFC generated by the PM.

3. Results and Discussion

3.1. Generation and Analysis of OFC

Based on the scheme in Section 2, an OFC optimization system by directly modulated DFB semiconductor laser based on cascaded electro-optic modulators is constructed, with the laser operating under gain-switching. Figure 2 shows the spectra of the initial gain-switched OFCs with different RF1 frequencies increasing from 4 to 10 GHz. When the frequency is set at 4 GHz, the spectrum exhibits significant broadening due to the frequency chirp effect, and no distinguishable spectral lines can be observed. As the frequency increases to 6 GHz, a comparison with the 4 GHz case reveals that the spectral width has narrowed. At 8 GHz, the spectral width continues to narrow relative to the 6 GHz case, and peaks begin to appear near the laser's optical frequency of 193.1 THz. When the frequency reaches 10 GHz, the spectral width narrows further, and distinguishable spectral lines appear in the spectrum, generating an OFC. The spacing between adjacent comb lines corresponds to the RF1 frequency, indicating that the laser's modulation frequency is near the ROF, which leads to the generation of periodic optical pulses.

Further research is conducted on the influence of different RF1 frequencies on the output spectrum of the DFB semiconductor laser. Figure 3a shows the number of distinguishable comb lines and the corresponding flatness for the RF1 frequency ranging from 10 to 20 GHz. The results indicate that as the RF1 frequency increases, the number of comb lines in the OFC gradually decreases, meaning that the spectral width decreases as the RF1 frequency increases. Meanwhile, the flatness of the generated OFC also changes accordingly with the change in RF1 frequency. The optimal overall performance in terms of the number of comb lines and flatness is obtained at a modulation frequency of 10 GHz. Beyond this frequency, although periodic optical pulse sequences can still be generated, the laser's frequency response decreases, resulting in a reduction in spectral width and the number of comb lines. Thus, the RF1 frequency of the DFB semiconductor laser is set at 10 GHz, and an initial OFC with seven spectral lines within 4.72 dB power variation is generated. The initial optical signal generated by DFB semiconductor laser is passed through PC1 and used as the input optical carrier signal for PM. The PS is set with a constant phase shift of 180°. Figure 3b shows the number of distinguishable comb lines in the PM output spectrum and the corresponding flatness for the EA gain ranging from 0 to 30 dB. The results indicate that as the EA gain increases, compared with the initial OFC comb lines

and their corresponding flatness generated by the gain-switched DFB semiconductor laser, the number of comb lines in the PM output signal gradually increases, meaning that the spectral width increases. However, the corresponding flatness mostly shows an increasing trend, indicating poor performance. Therefore, based on the initial OFC generated by the directly modulated DFB semiconductor laser through PM modulation, the optimization effect of spectral broadening, i.e., increasing the number of comb lines, can be achieved, but the flatness performance deteriorates.

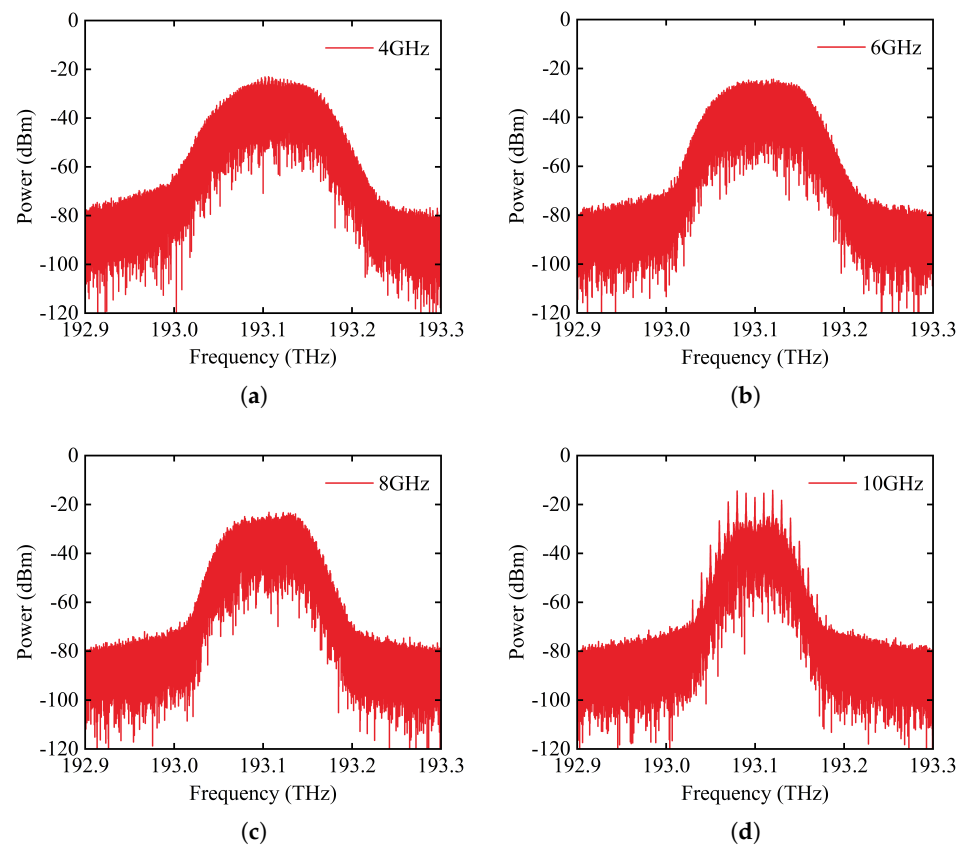


Figure 2. Optical spectra of the initial gain-switched OFCs with different RF1 frequencies of (a) 4 GHz, (b) 6 GHz, (c) 8 GHz, and (d) 10 GHz.

To address the issue of decreased flatness performance, this paper further proposes that the desired flatness optimization effect can be achieved by cascading an MZM after PM. The gain of the EA is set at 20 dB, and a 19-line OFC with a flatness within 5.63 dB is generated through PM. Meanwhile, the MZM half-wave voltage $V_{\pi, \text{MZM}}$ is 3.5 V, the insertion loss is 6 dB, and the extinction ratio is 30 dB. To meet the desired optimization requirements, MZM at the Minimum Transmission Bias Point (MITB) is excluded from consideration, as it suppresses the optical carrier and generates only odd-order sidebands. Therefore, we focus on the optimization effect of the OFC of PM output when the MZM is operated at the Maximum Transmission Bias point (MATB) and Quadrature Bias Point (QB). Figure 3c shows the change in OFC flatness with RF2 voltage, i.e., the modulation index, under different operating points of the MZM. When the MZM works at the MATB, the output signal contains optical carrier and even-order sidebands. Therefore, it is necessary to set the frequency of RF2 to half that of RF1, i.e., 5 GHz, and the applied bias voltage is set at 0 V. The results show that a small RF2 amplitude can improve the flatness of the OFC generated after PM. The flatness performance is improved when $V_{\text{RF2}} = 0.5$ V, and a 19-line OFC with a flatness within 5.14 dB can be generated. When the amplitude of RF2 is large, however, the flatness performance deteriorates, and the MZM cannot achieve the

optimization effect. When the MZM works at the QB, the output signal contains an optical carrier, odd-order sidebands, and even-order sidebands. Therefore, it is necessary to set the frequency of RF2 to the same value as RF1, i.e., 10 GHz, and the applied bias voltage is set at 0.875 V. The results show that a small RF2 amplitude can optimize the flatness of the OFC generated by PM. The flatness performance is optimal when $V_{RF2} = 1.2$ V, and a 19-line OFC with a flatness within 3.44 dB can be obtained. When the amplitude of RF2 is large, the flatness performance also deteriorates, and the MZM cannot achieve the optimization effect. By comparing the two operating points, it can be concluded that when the MZM works at the QB, it achieves a better optimization effect on the flatness of OFC from the PM, and the expected optimization goal can be achieved in a wide range of RF2 amplitudes. Under this condition, the two applied RF signals have the same frequency, and this consistent frequency relationship ensures that the phase coherence introduced by the gain-switching process is fully preserved throughout the subsequent modulation stages.

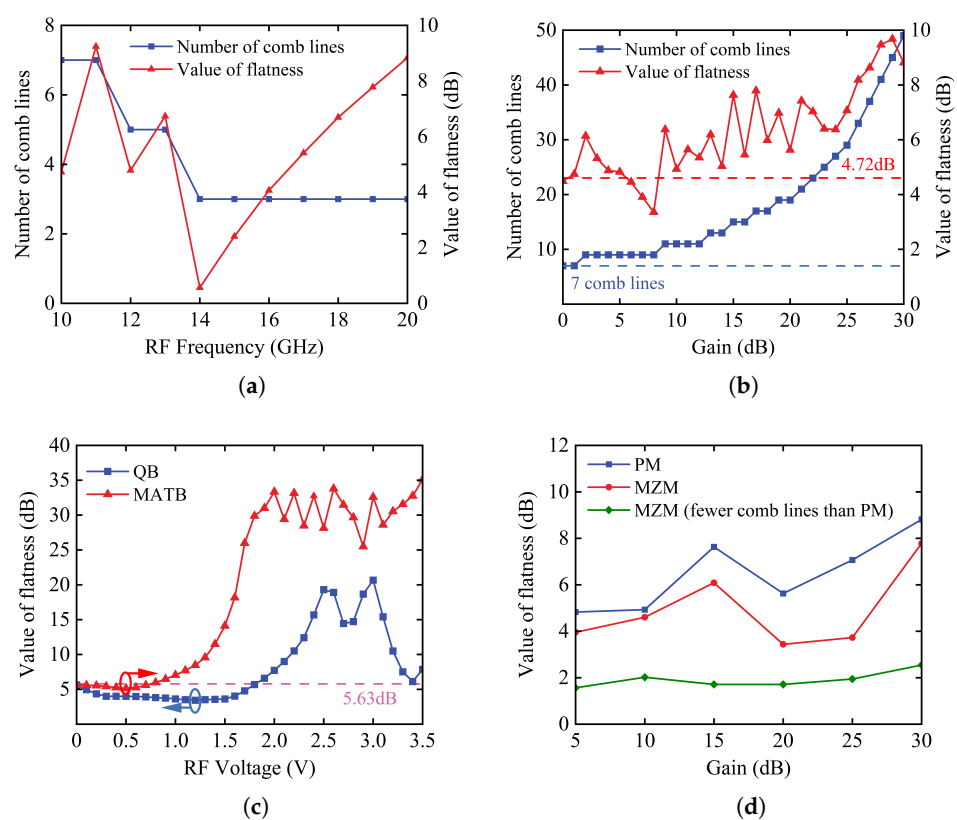


Figure 3. Impact of key parameters on generated OFC. (a) Impact of RF1 frequency on the number of comb lines and the corresponding flatness of OFC output from DFB semiconductor laser; (b) impact of EA gain on the number of comb lines and the corresponding flatness of OFC output from PM; (c) impact of RF2 voltage on the flatness of OFC output from MZM under different operating points; (d) comparison of flatness performance of OFC outputs from PM and MZM under different EA gains via the proposed optimization scheme.

To verify the general applicability of the proposed optimization scheme, further research is conducted on the flatness performance of the OFC generated by the gain-switched DFB semiconductor laser and optimized by the cascaded PM and MZM under different EA gains. The results are shown in Figure 3d, which indicate that by cascading the PM and MZM and adjusting the RF2 power and bias voltage of the MZM to operate it at the QB with an appropriate modulation index, the flatness performance can be optimized. Additionally, it can be observed that the MZM provides better optimization performance when one selects fewer comb lines from the MZM output than from the PM output.

Figure 4 shows the spectrum generated by a directly modulated DFB semiconductor laser based on the gain-switching effect when the frequency of RF1 is set at 10 GHz and the EA gain is set at 20 dB, as well as the spectra optimized by the cascade of PM and MZM. As shown in Figure 4d, the number of comb lines varies from 7 to 19, while the flatness initially degrades from 4.72 dB to 5.63 dB and subsequently improves to 3.44 dB. Moreover, a 17-line OFC with a flatness within 1.71 dB can be obtained with the bandwidth of 160 GHz. Additionally, the optical power of output signals decreases with the cascaded optimization, which can be compensated by incorporating an optical amplifier.

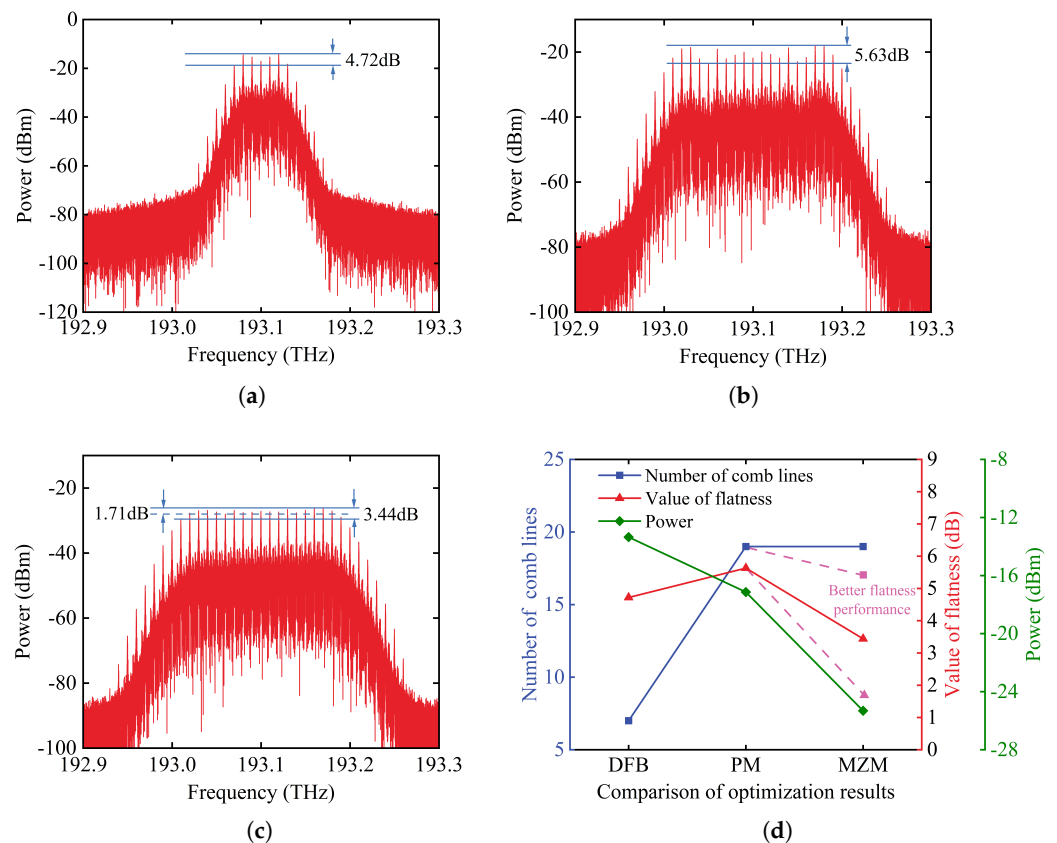


Figure 4. Results and analysis of the proposed scheme with the RF1 frequency set at 10 GHz and the EA gain set at 20 dB. (a) Output spectrum of DFB semiconductor laser; (b) output spectrum of PM; (c) output spectrum of MZM; (d) comparative analysis of optimization results.

Figure 5 shows the final OFC when the DFB semiconductor laser is not modulated with RF1, with the setup kept unchanged. As can be seen, only the 19-line OFC with a flatness within 10.27 dB and the 17-line OFC with a flatness within 9.56 dB can be obtained, which further demonstrates the superiority of the proposed scheme. Notably, significant temporal jitter is introduced through the proposed approach. Moreover, the large current modulation induces significant variations in the carrier concentration within the cavity, affecting the refractive index of the material and causing a dynamic change in the effective optical length of the laser cavity. This results in a dynamic chirp of the output optical frequency during the pulse duration, ultimately leading to a relatively low SNR of the generated OFC. Additionally, the frequency modulation noise of the OFC is related to the RF frequency, which can be further suppressed by increasing the frequency of RF. External optical injection can also improve the SNR of OFC. However, this technique introduces considerable system complexity and requires a high-quality seed laser, which is essentially equivalent to introducing an additional high-performance laser source.

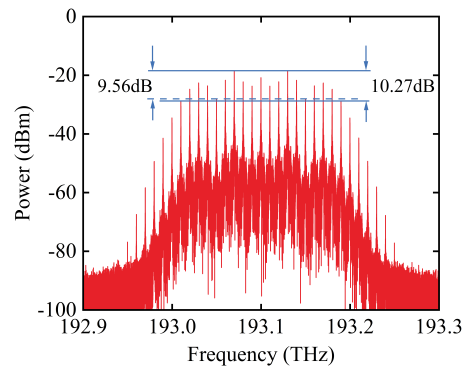


Figure 5. Optical spectrum of optimized OFC without directly modulating the DFB semiconductor laser for initial signal generation.

Additionally, we also demonstrated the optical spectra of the OFCs with a larger number of comb lines and excellent flatness performance obtained by our proposed scheme when the EA gain is set at 25 dB and 30 dB. As shown in Figure 6, a 27-line OFC with a flatness within 1.95 dB and a 45-line OFC with a flatness within 2.54 dB can be obtained, respectively.

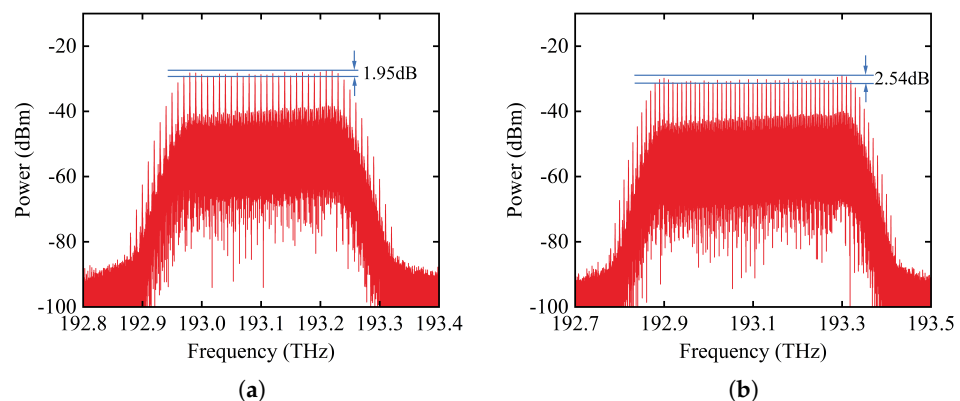


Figure 6. Optical spectra of the proposed scheme with the RF1 frequency set at 10 GHz and the EA gain set at (a) 25 dB and (b) 30 dB.

3.2. Optical Transmission System

The optimized OFC is adopted as the optical source for optical transmission systems, and the corresponding structural diagram is illustrated in Figure 7a. In the optical transmitter part, a 17-line OFC with a frequency spacing of 12.5 GHz and a flatness of 3 dB is generated as the optical source based on the proposed optimization scheme. The optical spectra of the OFC during the optimization process and the corresponding performance comparison are shown in Figure 7b,c, and then an erbium-doped fiber amplifier (EDFA) with a gain of 20 dB is employed for power amplification. The channel grid of the wavelength division multiplexing (WDM) system is dynamically reconfigurable. Here, the grid is set at 12.5 GHz, and the transmission rate is 2.5 Gb/s. The NRZ data signal is modulated onto the optical carrier via MZM. Demultiplexer (DEMUX) and multiplexer (MUX) are used to separate and couple spectral lines, respectively. For the fiber transmission link, single-mode fiber (SMF) is used for signal transmission, with a dispersion coefficient of 16 ps/nm/km. To compensate for dispersion, dispersion-compensating fiber (DCF) with a dispersion coefficient of -80 ps/nm/km is introduced after SMF. Additionally, for the power loss caused by optical fiber transmission, EDFA is also set at the front end of the link for power compensation, with its gain adjusted according to different fiber lengths. In the part of optical receiver, the received optical signal carrying NRZ information is demodu-

lated by a photodetector (PD) and a low-pass Bessel filter (LPBF), and the transmission performance is evaluated using a bit error rate analyzer (BERA).

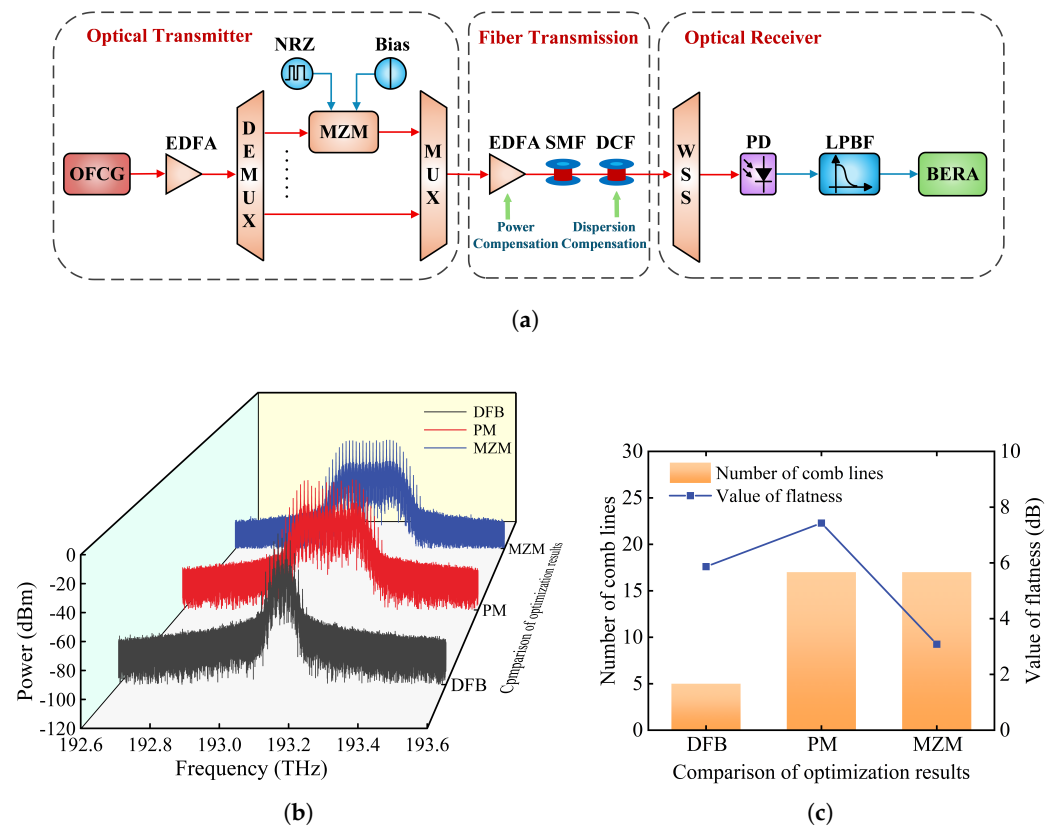


Figure 7. (a) Schematic diagram of the flexible-grid optical transmission system based on OFC; (b) output optical spectra at different stages of the proposed optimization scheme, where a 17-line OFC with a frequency spacing of 12.5 GHz and a flatness of 3 dB is generated; (c) performance comparison of the OFC at different stages. OFCG: optical frequency comb generator; EDFA: erbium-doped fiber amplifier; DEMUX: demultiplexer; MUX: multiplexer; NRZ: non-return-to-zero data signal; SMF: single-mode fiber; DCF: dispersion-compensating fiber; PD: photodetector; LPBF: low-pass Bessel filter; BERA: bit error rate analyzer.

Figure 8 shows the signal characteristics at key nodes of optical transmission performance based on the above system. In the back-to-back (BTB) case, the demodulated NRZ data signal is shown in Figure 9a. As can be seen, the original waveform is well recovered, and the BER is low at the order of 10^{-11} . The corresponding eye diagram is shown in Figure 9b. For another case, the SMF is set at 80 km with 16 km DCF in the link, the gain of EDFA is set at 19 dB, and the demodulated NRZ data signal after transmission is shown in Figure 9c. It can be seen that the data can still be almost completely recovered, and the BER is low at the order of 10^{-9} . The corresponding eye diagram is shown in Figure 9d. Compared with the BTB case, the opening degree of the received signal's eye diagram is reduced and the waveform becomes more distorted after 80 km SMF transmission, indicating some degradation in system performance. Nevertheless, the system can still meet the requirements for normal communication, and the BER variation remains within a relatively small range. Notably, for transmission systems utilizing an OFC as the multi-carrier optical source, the phase coherence among the comb lines is of critical importance for ensuring reliable transmission performance. The above transmission results over 80 km of SMF indirectly confirm that the OFC generated by our scheme has sufficient phase correlation for the demonstrated communication application, as severe phase decorrelation between comb lines would otherwise lead to significant performance degradation. The observed

eye diagram degradation after 80 km SMF transmission is primarily attributed to fiber chromatic dispersion.

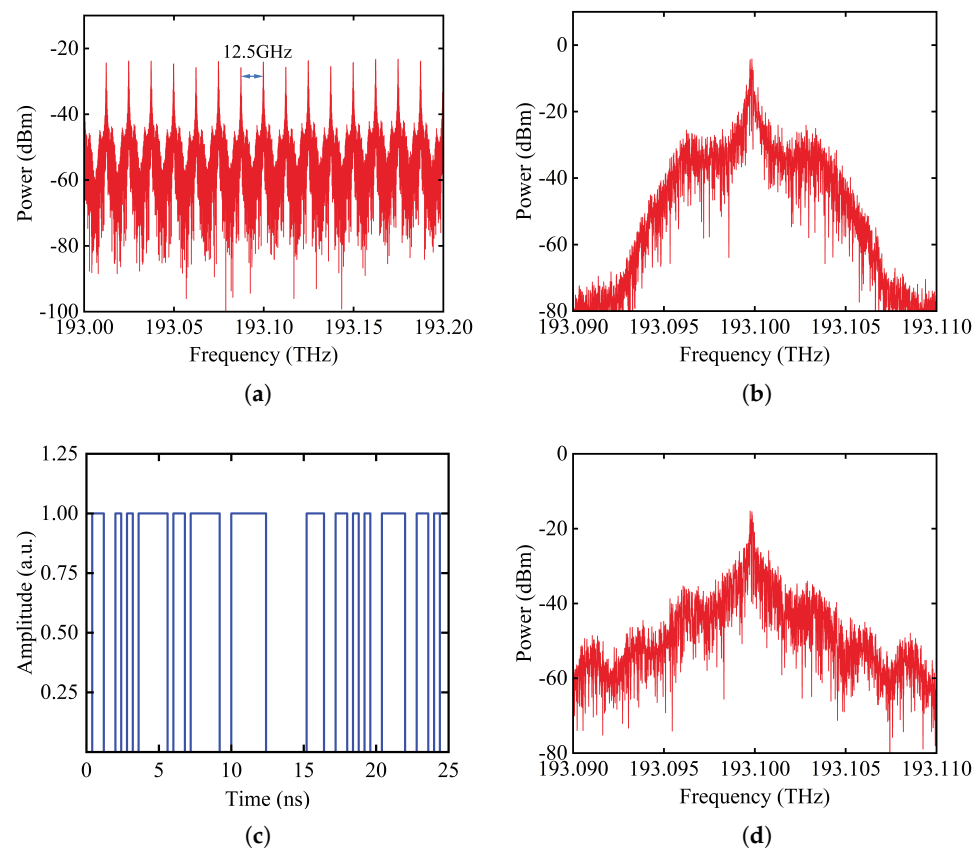


Figure 8. Signal characteristics at key nodes of the proposed flexible-grid optical transmission system based on OFC. (a) Partial zoomed-in view of the OFC spectrum output from the OFCG; (b) spectrum diagram of the center carrier extracted using DEMUX; (c) original NRZ digital baseband signal; (d) modulated signal with NRZ data information.

To enable a more rigorous evaluation of the system performance, the effect of transmission distance on BER is further discussed. Figure 10 shows the measured BER curves under different received optical powers and fiber lengths. The analysis results show that the receiver sensitivity is -24.44 dBm under the case of BTB transmission. For transmission distances of 50 km, 80 km, and 100 km over SMF, the corresponding lengths of DCF are 10 km, 16 km, and 20 km, respectively. The measured receiver sensitivities are -24.37 dBm, -24.31 dBm and -24.02 dBm, corresponding to power penalties of 0.07 dB, 0.13 dB and 0.42 dB, respectively. Theoretically, both fiber dispersion and transmission loss degrade the BER performance, and the receiver sensitivity typically decreases with the increasing transmission distance. In this system, however, dispersion is fully compensated by the DCF, effectively suppressing pulse broadening, while the EDFA serves to compensate for the link attenuation. As a result of both dispersion and attenuation being properly addressed, only minor variations in receiver sensitivity at different transmission distances are observed. Therefore, the proposed OFCG scheme exhibits reliable transmission performance and can find application in flexible-grid optical transmission systems.

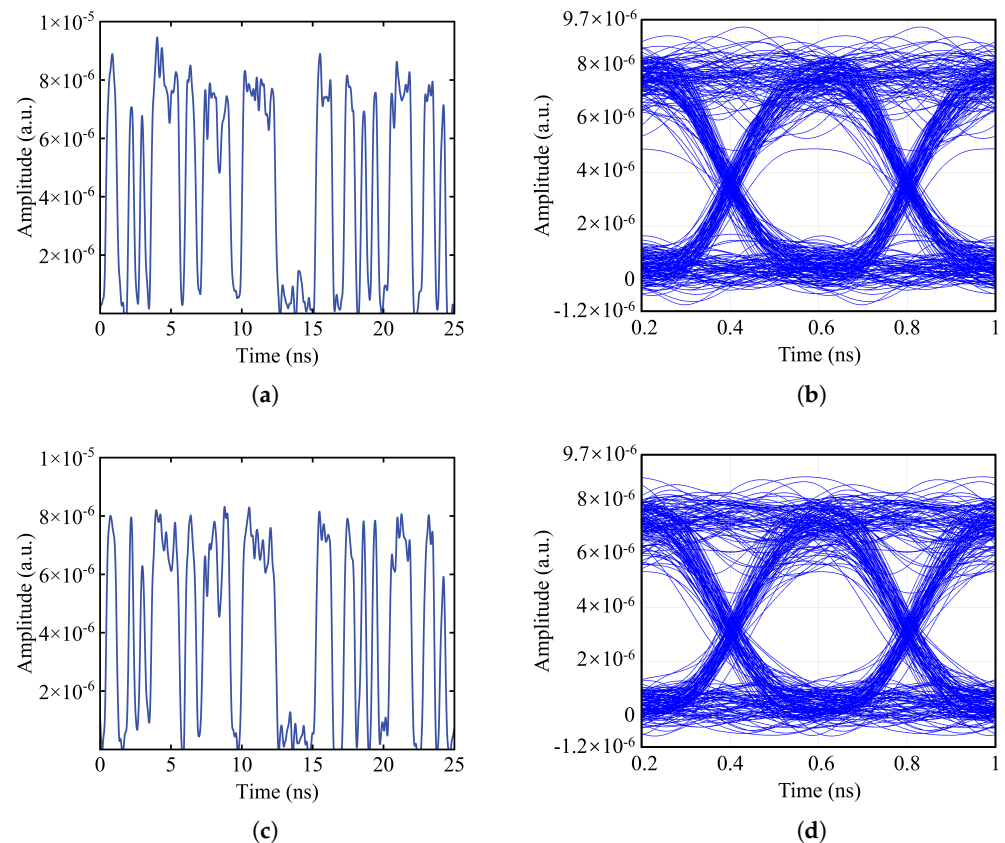


Figure 9. Waveforms and eye diagrams of demodulated NRZ data signal. (a) Waveform after BTB transmission; (b) eye diagram after BTB transmission; (c) waveform after 80 km SMF transmission; (d) eye diagram after 80 km SMF transmission.

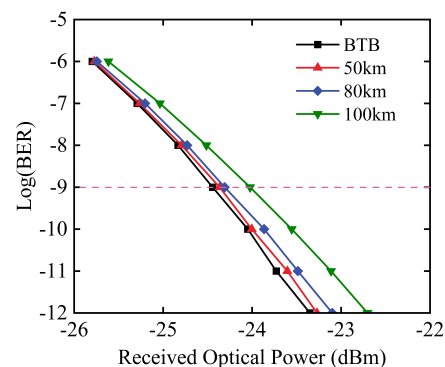


Figure 10. Impact of received optical power and fiber length on the system BER performance.

4. Conclusions

In this paper, a scheme for generating a broadened and flattened OFC based on a directly modulated DFB semiconductor laser cascaded with a PM and an MZM is proposed and demonstrated. Based on the gain-switching effect, the scheme directly modulates the DFB semiconductor laser to generate the initial OFC, expands the number of comb lines via a cascade PM, and optimizes the flatness performance via a secondary cascaded MZM. The comb spacing can be dynamically and flexibly tuned by adjusting the frequency of the RF signal, with a simple structure and low cost. The analysis results show that the proposed scheme can generate an initial OFC with seven spectral lines within 4.72 dB power variation. With the EA gain set at 20 dB, an OFC with 19 spectral lines within 5.63 dB power variation can be generated via PM, which is further optimized to 19 lines within 3.44 dB

and 17 lines within 1.71 dB via MZM. By further increasing the gain of EA, the proposed scheme can generate a 27-line OFC with a flatness of 1.95 dB and a 45-line OFC with a flatness of 2.54 dB, highlighting its ability to achieve a large number of comb lines while maintaining good flatness performance. Additionally, a 17-line OFC with a frequency spacing of 12.5 GHz and a flatness of 3 dB is generated as the multi-carrier optical source of flexible-grid optical transmission system based on the above scheme, where error-free transmission of a 2.5 Gb/s NRZ data signal is verified. The proposed scheme is easy to integrate and provides a cost-effective, tunable multi-carrier optical source in a flexible-grid optical transmission system.

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