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High-Performance Microwave-Frequency Comb Generation Based on Directly Modulated Laser with Filtering Operations

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Abstract: In this paper, a scheme for generating high-quality tunable microwave-frequency combs (MFCs) is proposed. The proposed scheme is based on an initially non-flat MFC generated by a directly modulated laser operating in gain-switching status. Filtering operations are used to increase the flatness of the MFC. Concretely, by employing an optical bandpass filter and a two-tap negative-coefficient microwave photonic filter, the flatness of the MFC is significantly optimized. In the experiment, MFCs with adjustable comb spacing from 0.5 GHz to 1.6 GHz and bandwidths ranging from 0 to 26.5 GHz are generated. The flatness is better than ± 2.5 dB for the MFC. The proposed scheme provides a simple, efficient, and high-performance solution for generating MFCs, making it a promising candidate for various applications requiring high-quality MFC sources.

Keywords: microwave-frequency comb; directly modulated laser; gain-switching status; filtering process



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1. Introduction

A microwave-frequency comb (MFC) is composed of equidistant, discrete microwave-frequency components with coherent and stable phase relationships. It has widespread applications in various fields, such as precision metrology, wireless communication systems, and radar systems [1–3].

Consequently, MFC generation has received considerable attention in recent years. In general, there are two main approaches for generating MFCs, including electrical methods and photonic-assisted methods. MFCs can be generated through electrical methods by taking advantage of the non-linear effects of electronic devices [1,4]. Although these methods exhibit compact systems, the resulting MFCs are limited in bandwidth due to inherent electronic bottleneck. In contrast, microwave photonic technologies provide a more compelling solution for MFC generation, owing to their inherent advantages such as broad operational bandwidth, low transmission loss, and robust immunity to electromagnetic interference.

Photonic-assisted methods for MFC generation typically comprise mode-locked lasers, optoelectronic feedback, electro-optic modulation, optical injection semiconductor lasers and non-linear driving of directly modulated lasers (DMLs). Mode-locked lasers have the ability to directly output a broad optical spectrum, and plenty of electrical spectral lines after photoelectric detection can be consequently generated [5–7]. However, they suffer from poor flatness. In optoelectronic feedback schemes, optoelectronic oscillators based

on actively mode-locked lasers have been widely studied to generate MFCs [8–12]. These approaches achieve relatively flat MFCs, but the bandwidth of the obtained MFC remains constrained by the limitations of the filter's bandwidth and amplifier's gain. Additionally, the comb spacing is determined by the ring length and is not easily adjustable over a wide range. MFCs generated based on electro-optic modulation technologies, such as cascaded modulation, exhibit significant advantages in terms of stability, wide frequency range, and good tunability [13–16]. However, drawbacks, such as high cost, system complexity, and high-power consumption, also limit their practical application. In schemes based on optical injection semiconductor lasers (OISLs), benefiting from the non-linear effects inside the lasers, a wideband MFC can be obtained [17–19]. However, the non-linear process of OISLs is usually not easy to control, and the generated MFCs also exhibit poor flatness. A scheme based on the nonlinear driving of a DML has been proposed to generate MFCs with a large number of spectral lines and a wide bandwidth [20]. However, the generated MFCs only have good flatness in a limited bandwidth, greatly reducing MFCs' availability.

Summing up the previous works, although successful demonstrations of MFC generation have been achieved, they show limitations in bandwidth, number of spectral lines, and flatness. In other words, these limitations are often difficult to solve simultaneously. Therefore, obtaining an MFC with a large bandwidth, good flatness, and high spectral line density is always a significant task.

In this work, a scheme based on direct modulation of a semiconductor laser and assisted filtering operations is proposed. Starting with an initial non-flat MFC generated by a DML operating in gain-switching status, the MFC's flatness is firstly optimized by using an optical bandpass filter (OBPF) to take out the flat part of the optical spectrum. Further optimization is achieved via a two-tap negative-coefficient microwave photonic filter (TT-NC MPF). The MFC's flatness is significantly enhanced from ± 13.28 dB to ± 1.97 dB within DC–26.5 GHz through these two operations. The comb spacing of the MFC is tunable within the range of 0.5 GHz to 1.6 GHz. This scheme is characterized by easy operation and superior results in generating MFCs, which may provide a promising high-performance MFC source.

2. Principle

The proposed MFC generation scheme is illustrated in Figure 1. The system consists of two main filtering modules, namely optical filtering and electrical filtering. The optical filtering is mainly realized by an OBPF, and the electrical filtering is implemented by constructing a TT-NC MPF. After the processing of these two filtering operations, the flatness of the MFC can be greatly improved, resulting in superior-quality MFCs.

First, let us consider the outputs of the DML when it is driven by a sinusoidal signal under different working statuses. Figure 2 illustrates the differences in waveform and spectra of a DML operating on normal driving status and gain-switching status. In Figure 2, I_{bias} represents the bias current of the DML, I_{th} is the threshold current, and I_{signal} denotes the modulation current converted from the RF intensity signal. The operational characteristics of the DML under normal driving status are depicted in Figure 2a. In this case, the conditions of $I_{bias} \pm |0.5 \times I_{signal}| > I_{th}$ are satisfied, and the DML acts at a linear modulation with a narrow optical spectrum. Therefore, just a few frequency components are generated. On the contrary, when the DML operates on the gain-switching status, the condition of $I_{bias} + |0.5 \times I_{signal}| > I_{th}$ is still satisfied, but $I_{bias} - |0.5 \times I_{signal}|$ remains below I_{th} and greater than 0 mA. In this condition, the relaxation oscillation dynamics of the semiconductor laser is dominant, enabling the DML to generate quasi-impulsive optical pulses [21–23] while simultaneously producing a broad but non-uniform optical spectrum [24,25]. Consequently, the generated MFC exhibits a dense distribution of frequency

components, as demonstrated in Figure 2b. Under this condition, the optical spectrum of the DML has a flat and wide part. Usually, a flat optical spectrum contributes to a flat electrical spectrum [26–28]. Therefore, the flat part of the optical spectrum can be utilized by optical filtering process to improve the flatness of the MFC, as illustrated in Figure 3. An OBPF is employed to extract the flat portion of the optical spectrum, which achieves the first optimization for the MFCs. However, the resulting MFC still exhibits the characteristic of higher amplitudes at low frequencies and lower amplitudes at high frequencies.

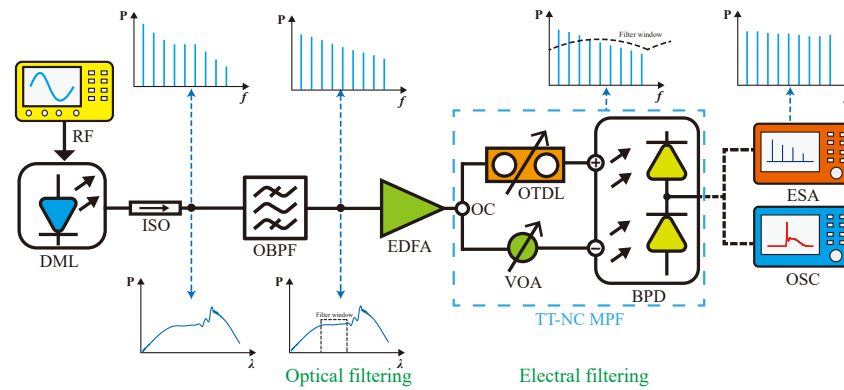


Figure 1. Schematic diagram of the proposed MFC generation scheme. RF, radio frequency source; ISO, isolator; EDFA, erbium-doped fiber amplifier; OC, optical coupler; OTDL, optical tunable delay line; VOA, variable optical attenuator; BPD, balanced photodetector; ESA, electrical spectral analyzer; OSC, oscilloscope.

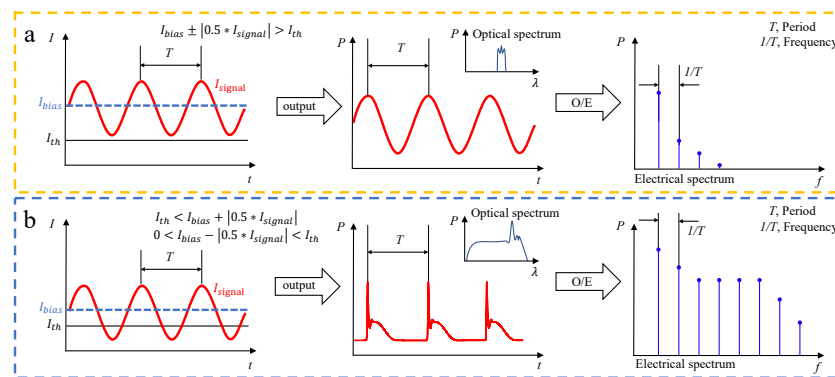


Figure 2. The diagram of a DML operating in different working statuses. (a) Normal driving status. (b) Gain-switching status.

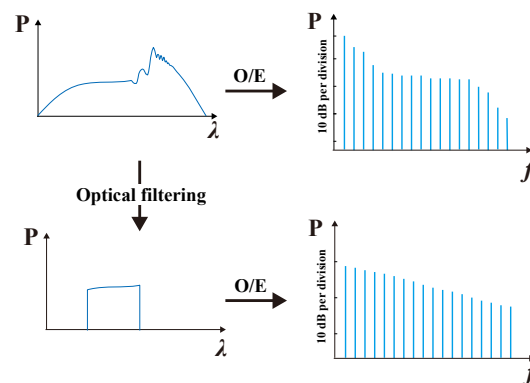


Figure 3. The comparison of the obtained MFC before and after optical filtering.

Based on this distinct characteristic above, a filter with low transmission at low frequencies and high transmission at high frequencies can be utilized to further improve the flatness of the MFC. Fortunately, the frequency response of the TT-NC MPF can precisely

meet this requirement. A TT-NC MPF is employed for the final optimization. The transfer function of the TT-NC MPF can be expressed as $A_P(f) = 1 - a \exp(-j2\pi\tau f)$, where a is the weight factor, f is frequency, j denotes the imaginary unit, and τ is the time delay. A microwave photonic filter without negative coefficients can only perform as a low-pass filter and cannot achieve filter responses with diverse characteristics. Therefore, incorporating negative coefficients is necessary. In the transfer function of the TT-NC MPF, the minus sign represents a negative coefficient. A negative coefficient corresponds to an inversion operation applied to the signal. The typical structure of TT-NC MPF is illustrated in Figure 4. There is one positive-coefficient tap and one negative-coefficient tap. Common methods for achieving the negative-coefficient tap include cross-gain modulation in semiconductor optical amplifiers, utilizing the positive and negative linear regions of a Mach–Zehnder modulator, and reversing the polarity at the photodetector. The method employed in this work utilizes the negative part of the BPD to realize the negative tap. This approach offers the advantage of simultaneously achieving signal inversion and optoelectronic conversion.

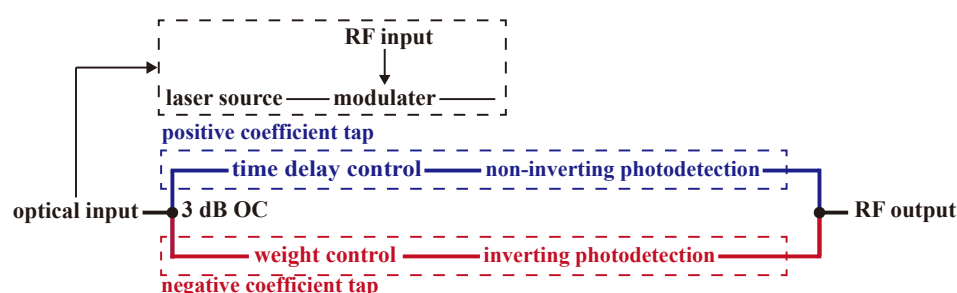


Figure 4. The typical structure of TT-NC MPF.

For a TT-NC MPF, the weight and time delay are important parameters, where τ determines the FSR ($\text{FSR} = 1/\tau$) and a determines the filtering depth. By adjusting the time delay and weight factor, the influence of these parameters on the frequency response of the microwave photonic filter can be observed, as illustrated in Figure 5. By appropriately tuning a and τ , the MFC can be effectively optimized through MPF filtering, thereby obtaining a higher flatness of the electrical spectrum. It should be noted that the fluctuation of the MFC spectral profile should not be too large for the TT-NC MPF when it is employed to shape the non-flat MFC. In this way, the power of the low-frequency components is partially suppressed, while that of the high-frequency components is hardly attenuated, and the flatness of the MFC is further optimized, as shown in Figure 6.

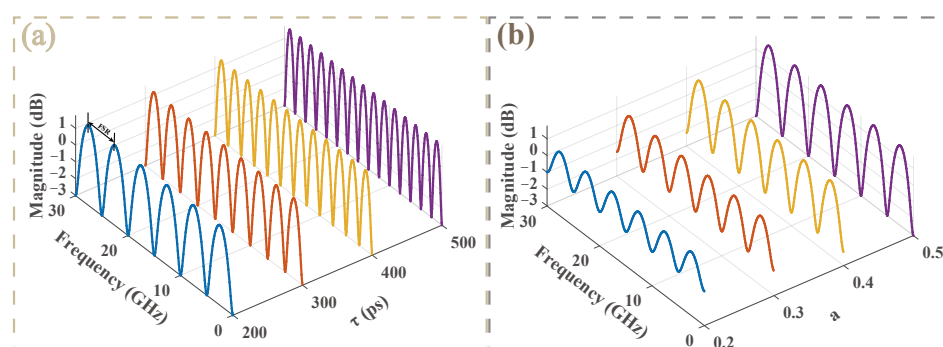


Figure 5. Frequency response of TT-NC MPF to changing a and τ . (a) Same a , different τ . (b) Same τ , different a .

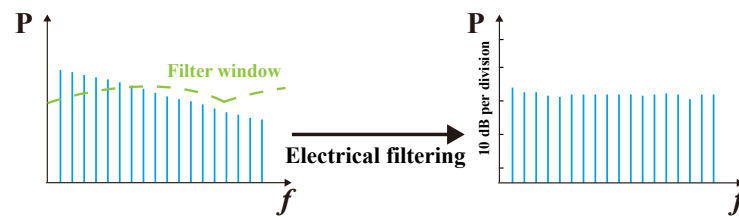


Figure 6. The comparison of the obtained MFC before and after electrical filtering.

3. Experimental Results and Discussion

To verify the feasibility of the proposed scheme, an experiment based on the setup shown in Figure 1 is carried out. The experimental results, including the waveform, optical spectrum, and electrical spectrum, are measured using an OSC (Agilent Technologies, Santa Clara, CA, USA 86100D), an optical spectrum analyzer (OSA, YOKOGAWA, Tokyo, Japan, AQ6370C), and an ESA (Agilent Technologies N9010A), respectively. The DML (CONQUER, Beijing, China KG-DML-9040) has a center wavelength of 1547.6 nm and a threshold current of 30 mA. It operates at 25 °C and is biased at 36 mA. The RF generator (Keysight, Santa Clara, CA, USA E8257D) outputs a sinusoidal waveform with a repetition frequency of 500 MHz and a power of 18 dBm to drive the DML. Under these conditions, the expected gain-switching status occurs, which results in a pulse-like waveform, and a broad optical and electrical spectrum, as shown in Figure 7. As can be observed, the time-domain waveform exhibits the relaxation oscillation spikes, while the optical spectrum shows a flat low-power region and an uneven high-power carrier section. The corresponding electrical spectrum is indicated in Figure 7c, which is a non-flat MFC and has a flatness of ± 13.28 dB with a bandwidth of 0–26.5 GHz.

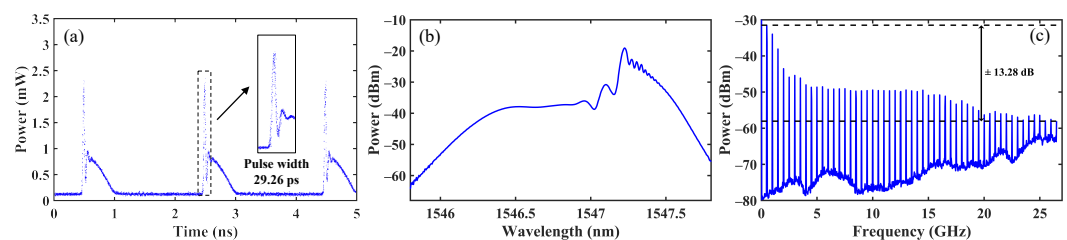


Figure 7. Results of gain-switching status of DML driven by 500-MHz sinusoidal signal. (a) Waveform. (b) Optical spectrum. (c) Electrical spectrum.

As previously analyzed in the theory, a flatter optical spectrum contributes to a flatter electrical spectrum. Therefore, an OBPF (Alnair, Tokyo, Japan, Labs bvf-300cl) is employed to filter out the flat part of the optical spectrum, as shown in Figure 8. Due to the power loss caused by the optical filtering process, an EDFA is utilized to amplify the optical power for compensating power loss. The amplified signal is then entered into a TT-NC MPF, which is composed of a 3 dB OC, a VOA, an OTDL (Luna, Roanoke, VA, USA VDL-001), and a BPD (Coherent, Saxonburg, PA, USA BPDV2120R). The electrical spectrum and time-domain waveforms of the two taps are illustrated in Figure 9. For both the positive and negative output of the BPD, only the waveform is inverted. In other words, a phase difference of π is introduced between the two taps. However, this phase change does not modify the shape of the optical spectrum, and consequently, the shape and trend of the electrical spectrum remain unaffected, which is very beneficial for TT-NC MPF.

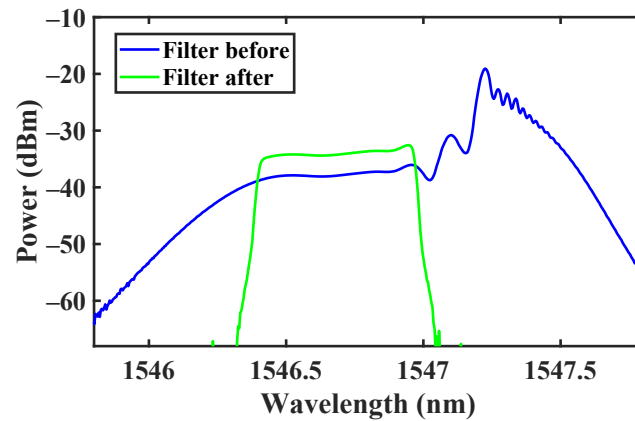


Figure 8. The flat part of the optical spectrum is filtered out through an OBPF.

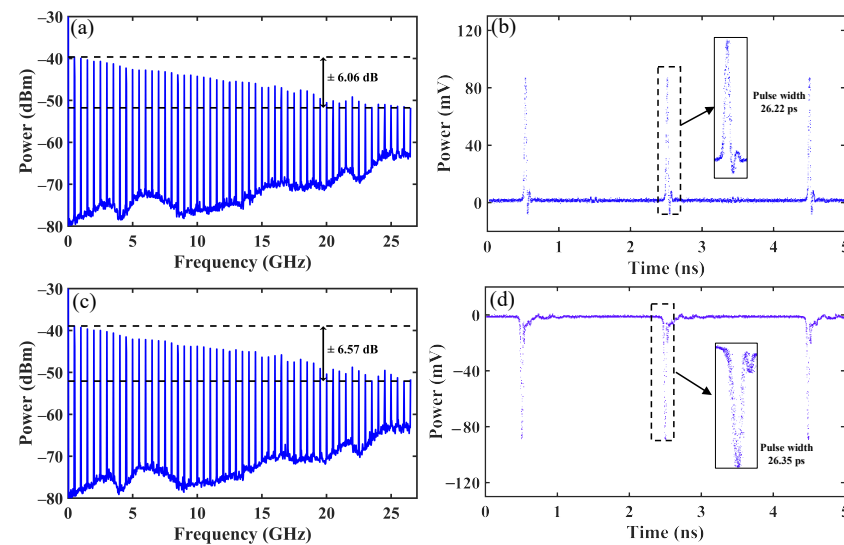


Figure 9. The electrical spectrum and waveforms of the two taps. (a) The positive output waveform of BPD. (b) The corresponding electrical spectrum. (c) The negative output waveform of BPD. (d) The corresponding electrical spectrum.

In the TT-NC MPF, the weight factor is adjusted by the VOA, and the time delay is tuned by the OTDL. To facilitate the observation of the filtering effect of MPF, by keeping the weight factor unchanged, by adjusting the time delay, the output results are observed, as shown in Figure 10a,b. From these figures, it can be clearly seen that under different time delay settings, the filtering curves and their trends of the MPF are distinct. Thus, certain optimization results can be achieved by adjusting the time delay. Similarly, by fixing the time delay and adjusting the power ratio between the two split paths, the results shown in Figure 10c,d are obtained. As can be observed, when the time delay is optimized to its best value, further optimization can be achieved by adjusting the power.

Consequently, by sequentially adjusting the time delay ($\tau = 24$ ps, FSR = 41 GHz) and weight factors ($a = 0.203$), the final result is obtained, as shown in Figure 11. Obviously, the MFC with an initial flatness of 13.28 dB is successfully optimized to ± 1.97 dB, which achieves a significant performance improvement of 22.62 dB (corresponding to 182.81 times). In addition, the clean waveform also indicates that stable phases are existed among these spectral lines.

To further exhibit the tunability of the system, the repetition frequencies of the RF signal are set from 600 MHz to 1.6 GHz, with a step of 200 MHz, respectively. By correspondingly altering the time delay and power ratio, the tunable MFCs are achieved, as shown in Figure 12, which also demonstrate excellent performance.

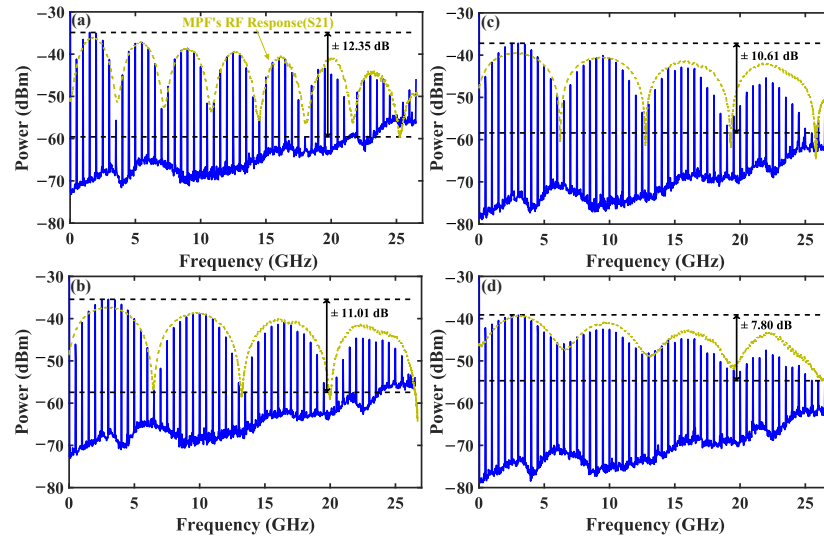


Figure 10. (a,b) Results under equal power ratio ($a = 0.487$) and different time delays ($\tau_a = 274$ ps, $\text{FSR}_a = 3.66$ GHz; $\tau_b = 143$ ps, $\text{FSR}_b = 6.99$ GHz). (c,d) Results under equal time delay ($\tau = 154$ ps, $\text{FSR} = 6.49$ GHz) and different power ratios ($a_c = 0.451$, $a_d = 0.350$).

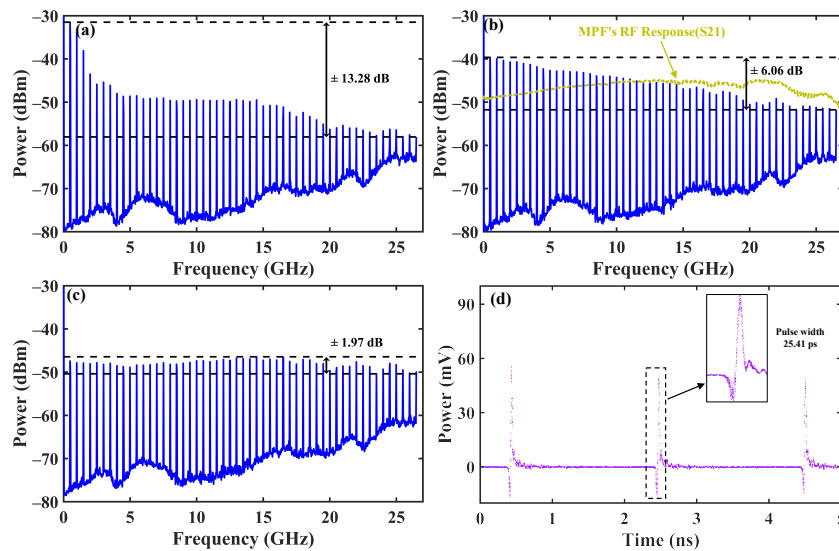


Figure 11. The electrical spectrum and waveform of the final MFC. (a) The initial spectrum. (b) The spectrum after optical filtering. (c) The result of flat spectrum. (d) The corresponding waveform. Flatness calculation method: peak-to-peak value within the MFC bandwidth range.

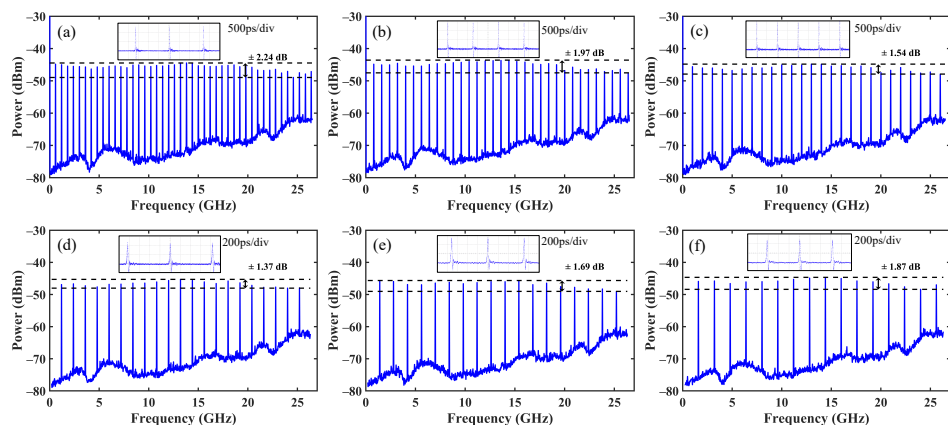


Figure 12. The tunable MFCs with different repetition frequencies of the RF signal: (a) 600 MHz; (b) 800 MHz; (c) 1000 MHz; (d) 1.2 GHz; (e) 1.4 GHz; (f) 1.6 GHz.

The single-sideband (SSB) phase noise was measured by ESA, as illustrated in Figure 13. The trends of the phase noise at every 1 GHz interval for MFC with a comb spacing of 500 MHz are plotted in Figure 13a. It is observed that the phase noise deteriorates to some extent at higher frequencies. This degradation is likely due to the increased high-frequency noise floor of the ESA and the power attenuation of the MFC at higher frequencies. Figure 13b presents the phase noise of MFCs with different comb spacings as verified in the experiment. The phase noise of MFCs with different comb tooth spacings at frequency offsets of 10 kHz and 1 kHz is summarized in Figure 13c. The phase noise trends of MFCs with different comb spacings are generally consistent, with phase noise lower than -97 dBc/Hz@1 kHz and -101 dBc/Hz@10 kHz. This indicates that the phase noise performance of the generated MFCs can be stably maintained with a comb spacing range of 0.5–1.6 GHz.

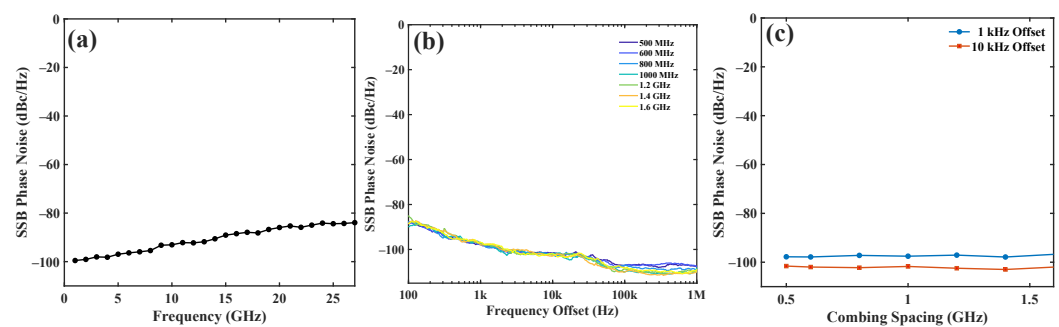


Figure 13. (a) SSB phase noise of MFC with 500 MHz comb spacing at 10 kHz offset; (b) SSB phase noise spectra; (c) phase noise at 1 kHz offset and 10 kHz offset for MFCs with different comb spacings.

Through the above experimental demonstrations, the flatness of the resulting MFC is greatly optimized assisted by two filtering operations. It is worth mentioning that the negative tap in the MPF can be implemented in an all-optical way, such as using cross-gain modulation in a semiconductor optical amplifier. BPD may be removed by combining with a polarization superposition structure. This proposed scheme is expected to achieve the desired MFC generation entirely in the optical domain. Compared to existing works, this scheme is simpler to operate and gives the resulting MFC significant improvements in the number of comb lines, flatness, and bandwidth. The performance metrics are superior, which provides a candidate for high-performance MFC sources. High-performance MFC sources have numerous potential applications, such as the recently reported microwave detection technology based on Rydberg atoms [3,29]. Combined with MFCs' ability to decompose signals into equally spaced frequency components for parallel multi-frequency analysis, it enables efficient broadband signal monitoring and accurate analysis. Since the bandwidth of the ESA used is only 26.5 GHz, the experimentally obtained MFC is limited to 26.5 GHz. Theoretically, however, the MFC generated in this scheme may have a much wider bandwidth due to the broad optical spectrum.

4. Conclusions

In summary, a scheme for generating MFCs is proposed and experimentally demonstrated. The MFC directly generated by a DML can be significantly enhanced with the assistance of optical and electrical filtering. The MFC with an initial flatness of ± 13.28 dB is successfully optimized to ± 1.97 dB, and a significant performance improvement of 22.62 dB is achieved. Since the DML is the most popular device, the system features a simple structure and ease of tuning, providing an attractive solution for MFC generation.

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