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Research on Optical Mutual Injection to Generate Tunable Microwave Frequency Combs

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Abstract: In this study, a scheme for generating tunable microwave frequency combs (MFCs) based on optical mutual injection is proposed and experimentally investigated. The scheme is based on the optical injection of lasers to generate MFCs, and constitutes a feedback loop by using dual-laser mutual injection to obtain MFCs with a large continuous bandwidth and tunable comb spacing. The experimental setup analyzes the effects of injected optical power, modulation frequency and amplitude, and wavelength detuning on the generated MFC signals. The experimental results indicate that when the single-frequency electrical signal is set to 2 GHz, flat MFCs with amplitude variations within 10 dB can be obtained by optimizing the injected power and the frequency detuning between the two semiconductor lasers. Furthermore, the comb spacing of the MFCs can be made tunable by varying the modulation frequency and selecting the matched operating parameters to adapt to different application scenarios.

Keywords: microwave frequency comb; optical mutual injection; frequency detuning; tunable comb spacing; semiconductor laser

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1. Introduction

Microwave frequency combs (MFCs) can simultaneously provide multiple microwave signals with varying frequencies. This technology boasts several advantages, including excellent signal flatness and broad frequency coverage. Thus, MFCs can be applied in diverse fields such as satellite communication, remote sensing, frequency measurement, and anti-interference detection [1,2]. For instance, near-Earth space has become increasingly crowded by a significant number of military and civilian satellites, resulting in challenges such as depleted orbital resources and congested communication bands. Specially, military satellites must switch frequency bands to ensure the utmost security of information. Broadband MFC signals have the capability to simultaneously cover C, Ku, Ka, and other frequency bands, thereby meeting the requirements of multi-band frequency conversion [3,4]. Therefore, the pursuit of an ultra-flat MFC with a wide frequency range and tunable frequency spacing has emerged as a prominent focus within the field of microwave technology.

Up to now, MFCs have mainly been generated using two approaches: electrical methods and optoelectronic methods. Methods of generating MFCs by electrical means mainly use the nonlinear effect of electronic devices, such as varactor diodes, step recovery diodes (SRDs), nonlinear transmission lines (NLTLs), and other nonlinear devices. Narrow pulse signals driven by low-frequency signals are generated to obtain MFCs in the frequency domain; however, due to the limitations of the components' electronic bandwidth, the generated MFC bandwidths are small and the high harmonic frequency components are drastically reduced, which is not conducive to meeting the demands for ultra-wideband MFC signals in practical applications.

With the advancement of microwave photonics, methods based on optoelectronics have been proposed to generate MFCs. Three approaches are frequently used: one is based on scanning tunneling microscope (STM) tunnel junctions [5,6]; the second is based on the use of photodetectors (PDs) to beat the frequency of the optical frequency comb [7]; and the third is based on the nonlinear dynamical state presented by semiconductor lasers (SLs) under a suitable external perturbation. Due to the high complexity of the experimental systems used in the first two approaches, the acquired MFC bandwidth is relatively small, the comb spacing is not easily adjustable, and it is difficult to ensure that the power between the comb lines is balanced. Therefore, most studies in recent years have used the third method to generate high-quality MFC signals, such as optical injection [8,9], optical feedback [10], and photoelectric feedback [11–13]. For instance, Fan et al. proposed a scheme to generate MFCs based on current-modulated optical injection. However, the comb lines in the low-frequency range of 0 GHz–8.4 GHz exhibited strong power compared with other frequencies, necessitating the need for filtering these comb lines during output [14]. Additionally, Zhang et al. presented a scheme to obtain MFCs using an optically injected semiconductor laser with dual-loop optoelectronic feedback. The introduction of two feedback loops led to a more complex experimental system, resulting in poorer flatness of the comb lines [15]. Furthermore, Zhao et al. proposed the utilization of integrated mutual-coupled distributed feedback lasers to generate broadband microwave combs with tunable frequency. The maximum bandwidth achieved was 15 GHz, and the control mode of the system was relatively complex [16]. In the same year, Zhao et al. proposed a scheme to generate microwave frequency combs by using a single optical injection semiconductor laser, but the central wavelengths of the two lasers need to be kept consistent [17].

Schemes based on SLs to acquire MFCs under external perturbations have been investigated, but most of them are based on unidirectional injection, while studies based on mutual injection to generate ultra-wideband high-quality MFCs have not been reported. In light of this, the present study proposed a scheme based on optical mutual injection to generate tunable MFCs. This approach involves adding two lasers into a loop structure to obtain an MFC with a large continuous bandwidth and tunable comb spacing. This study experimentally analyzes the effects of injected optical power, modulation signal frequency and amplitude, and wavelength detuning on the generation of MFC signals. By changing the frequency of the single-frequency electrical signal and selecting matching operating parameters, a tunable broadband MFC with tunable comb spacing can be achieved. Furthermore, this study analyzes the performance advantages of the proposed scheme in terms of MFC signal bandwidth and flatness compared with the unidirectional optical injection laser scheme. These results confirm the feasibility of the proposed mutual injection method for generating tunable MFCs.

2. Principle and Experimental Setup

SLs are particularly sensitive to external perturbations. By appropriately varying the injection intensity and frequency detuning between lasers, the output can be made to exhibit a series of complex dynamical states, including period-one oscillation (P1), period-doubling oscillation (P2), quasiperiod oscillation, and chaos. Of these, the P1 state of the laser can be used to generate MFC signals and has unique advantages. Therefore, this study proposes a tunable MFC generation scheme based on optical mutual injection, and the experimental setup is illustrated in Figure 1.

The system comprises two SLs, two optical circulators (OCs), two variable optical attenuators (VOAs), two polarization controllers (PCs), a Mach–Zehnder modulator (MZM), and two erbium-doped fiber amplifiers (EDFAs), among other necessary components. By adjusting the attenuation coefficient of the VOAs and the center frequency difference between the two SLs, the power and frequency detuning of the injected light can be modified. This, in turn, leads to changes in the laser output and results in the laser exhibiting various dynamic states.

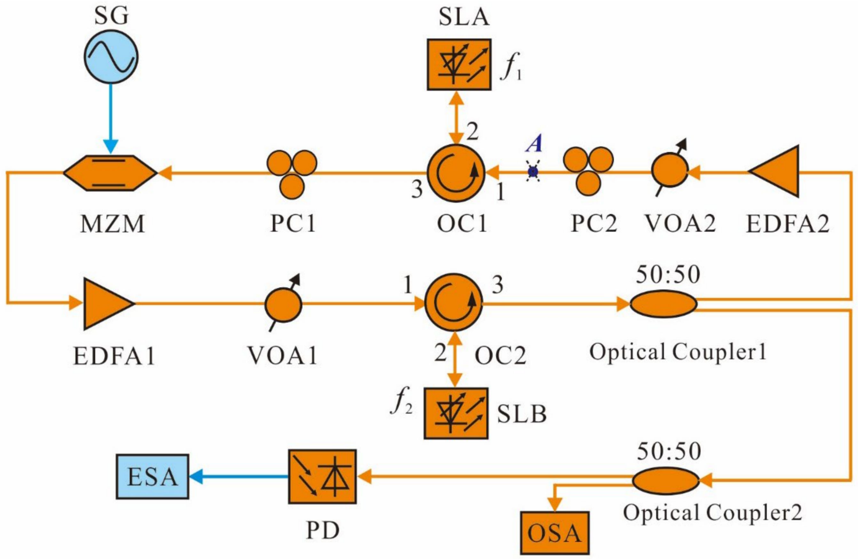


Figure 1. Experimental setup. SL: semiconductor laser; OC: optical circulator; PC: polarization controller; MZM: Mach–Zehnder modulator; SG: signal generator; EDFA: erbium-doped fiber amplifier; VOA: variable optical attenuator; OSA: optical spectrum analyzer; PD: photodetector; ESA: electrical spectrum analyzer.

In the experiment, both semiconductor laser A (SLA) and semiconductor laser B (SLB) were distributed feedback (DFB) semiconductor lasers. The optical power and center wavelength of SLA were controlled by a current source (ILX Lightwave, LDX-3412, Newport, Irvine, CA, USA) and a temperature controller (3040, Newport, Irvine, CA, USA), while SLB's optical power and center wavelength were regulated by a current–temperature controller (ILX Lightwave, LDC-3724B, Newport, Irvine, CA, USA). The optical signal generated by SLA was coupled to port 2 of OC1, and its polarization state was controlled by PC1 after output, being outputted from port 3. A sinusoidal signal with a frequency ranging from 0.5 GHz to 10 GHz was produced by the signal generator (83592A, HP, Palo Alto, CA, USA) and modulated to the optical domain through an electro-optical modulator (F-10, Avanex, Fremont, CA, USA). The modulated optical signal was then amplified by an EDFA and entered VOA 1 (HA9, JDS FITEL, San Jose, CA, USA) in order to control the intensity of the injected optical signals.

Following the power adjustment, the optical signal was directed into port 1 of OC2 and injected into SLB through bidirectional channel 2. The bandwidth-enhanced optical signal generated by SLB was routed back to OC2 through port 2 and then output from port 3 to the 50:50 optical coupler 1, where it was split into two equal parts. One part of the optical signals was transmitted through various devices, such as EDFA2, VOA2, and PC2, to adjust its injected optical power and polarization state. Finally, it was injected back into SLA via ports 1 and 2 of OC1, forming a ring structure with a mutual injection of optical signals. The other part of the optical signal was used for observing signal quality. After passing through optical coupler 2, its spectrum was analyzed using an optical spectrum analyzer (70001A+70952B, HP, Palo Alto, CA, USA). Simultaneously, it was fed into a photodetector (MPRV1331A, U2T, Berlin, Germany) with a bandwidth of 31 GHz for photoelectric conversion, and then the output electrical signal was passed through an electrical spectrum analyzer (FSEK20, Rohde & Schwarz, Munich, Germany) to observe the spectrum, allowing for the analysis of the signal quality of the output MFC.

The frequency ranges of the sinusoidal signal generated from the signal generator were within the range of 0.5 GHz to 10 GHz. To adjust the injected optical power over a wide range, it was necessary to amplify it by using an EDFA with an initial gain of 10 dB. The VOA was employed to regulate the optical power injected into the two lasers, with an initial attenuation coefficient of 11 dB. The photodetector with a transimpedance amplifier was biased to a voltage of +3.3 V, and the voltage of the transimpedance amplifier was also +3.3 V.

In this study, the quality of the generated MFCs was evaluated by employing a continuous bandwidth and flatness. The continuous bandwidth of an MFC is defined as the continuous frequency range over which the comb amplitude varies less than a certain threshold. In this study, this threshold was set to 10 dB, i.e., the maximum power value minus 10 dBm, and the MFC component within this range was the bandwidth [8]. The flatness is the maximum value of the power difference between all combs in the continuous bandwidth range. Since optical injection into SLs to generate MFCs mainly utilizes their period-one oscillation (P1) characteristics, they are sensitive to variations in injection intensity and frequency detuning. Then, we proceeded to experimentally investigate the effects of injection power, modulation signal frequency and amplitude, and frequency detuning on the output MFC signals in order to identify the system parameters with the optimal performance.

3. Experimental Results

3.1. Mutual Injection versus Unidirectional Injection

First, the performance differences between the unidirectional injection scheme and the proposed mutual injection scheme are experimentally compared. As shown in Figure 1, the ring system was disconnected at point A to cut off the signal light injected into SLA, thereby transforming the mutual injection scheme into a unidirectional injection scheme. Using identical experimental conditions, we proceeded to compare the quality of the MFC signals generated by both schemes. The sinusoidal signal frequency from the signal generator was set to 2 GHz with an amplitude of 0.8 V. The operating parameters for the current source of SLA were 74.6 mA and 21.2 °C, while for SLB, they were set to 34.5 mA and 22.03 °C, ensuring consistency in parameters such as injected optical power, modulation signal, and wavelength detuning. The MFC spectra obtained from the unidirectional and mutual injection methods are shown in Figure 2a,b, respectively.

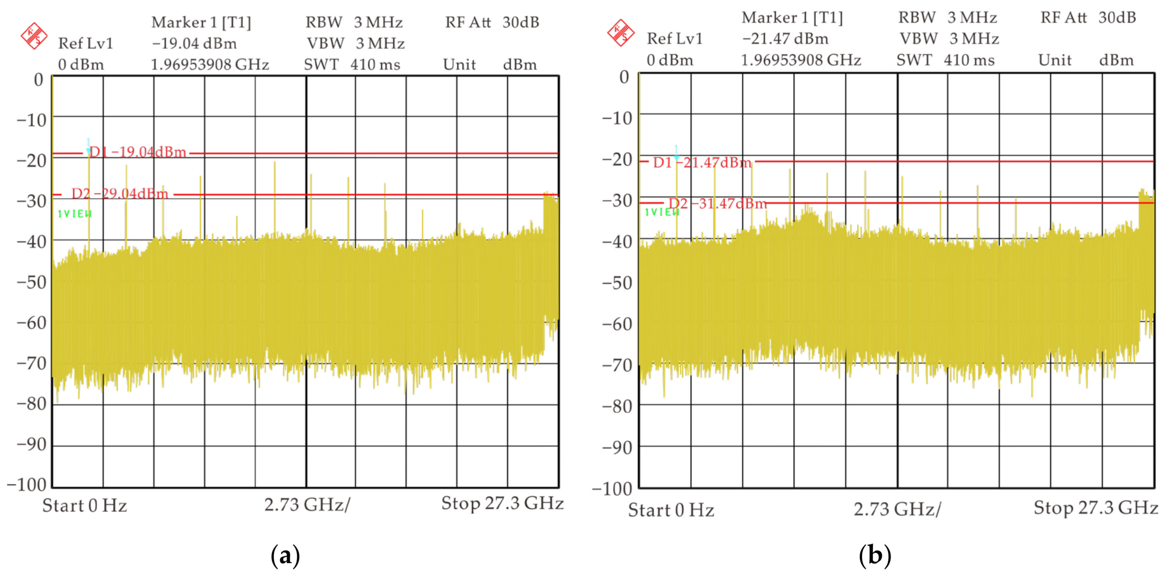


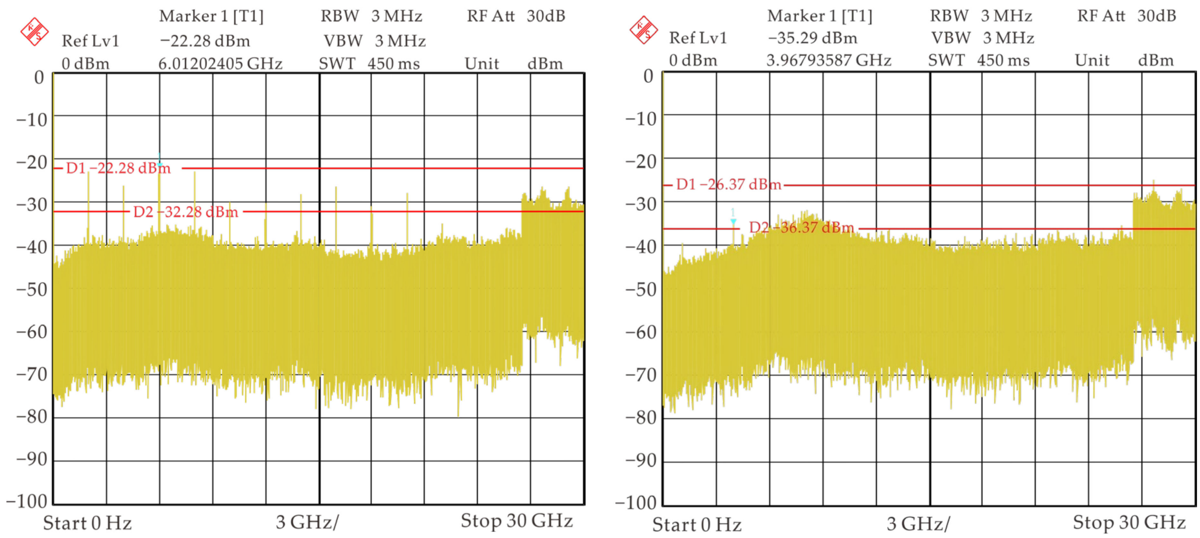
Figure 2. Comparison of MFCs generated by unidirectional injection (**a**) and mutual injection (**b**).

The bandwidth of an MFC can be determined by an electrical spectrum analyzer as follows. The component with the highest comb power is found directly through the peak-finding function of the electrical spectrum analyzer. This component has a frequency of 2 GHz and a power of −19.04 dBm, which is the first comb line of the MFC. In this study, the bandwidth threshold of the MFC was defined as 10 dB, and the upper bound was determined by plotting an isoline with a power of −19.04 dBm. Then, an isoline with a power of −29.04 dBm was drawn to determine the lower bound. As shown in Figure 2a, there are four comb line components between the two power contours, which contribute to a bandwidth of 8 GHz for the MFC and a relatively small bandwidth due to the excessive comb line power in the low-frequency band, whereas the bandwidth of the MFC signal generated by the mutual injection method is extended to 20 GHz and the number of comb lines is increased to 10. In this scenario, the maximum power at the low-frequency range is −21.47 dBm, and the power distribution among the comb lines is more balanced, resulting in a flatter MFC signal.

This enhancement is attributed to the fact that the oscillation energy generated by optical mutual injection is distributed not only in the chirp oscillation frequency region but also induces high-frequency periodic oscillations due to the beat-frequency effect, thereby balancing the power distribution between low-frequency and high-frequency regions. In conclusion, compared to the unidirectional optical injection scheme, the proposed approach significantly improves the bandwidth and flatness of the MFC signal by introducing optical mutual injection, which effectively redistributes the energy among the comb lines.

3.2. Effect of the Injection Optical Power on MFCs

To investigate the impact of the injected optical power on the generated MFC, the attenuation coefficient of VOA1 was adjusted while keeping the initial parameters unchanged. The optical signal intensity injected into SLB was thus controlled. In the experiment, the VOA1 attenuation coefficient ranged from 0.5 to 13.5 dB, with a step size of 1 dB, and the VOA2 attenuation coefficient was set to 5.5 dB. The MFC signals were observed using an electrical spectrum analyzer. When the modulation frequency was set to 2 GHz, Figure 3a,b show the MFC spectra obtained for the VOA1 attenuation coefficients of 3.5 dB and 13.5 dB, respectively. Additionally, Figure 4 illustrates the effect curves of different attenuation coefficients on both the MFC bandwidth and maximum power.



(**a**) (**b**)

Figure 3. Electrical spectrum of the MFC when the modulation frequency is 2 GHz and the attenuator coefficient of VOA1 is 3.5 dB (**a**) and 13.5 dB (**b**).

According to Figure 3, it is evident that when the attenuation value is set to 3.5 dB, the resulting MFC signal exhibits a bandwidth of 20 GHz with 10 comb lines, and the maximum power is −22.28 dBm. The spacing between comb lines is 2 GHz, and the power distribution along the comb is relatively balanced, resulting in a flat signal. At this specific attenuation value, the quality of the MFC signal is optimal. However, as the attenuation coefficient increases gradually, the output signal quality deteriorates. Once the attenuation coefficient reaches 13.5 dB, the low-frequency component of the signal experiences a significant power drop, and the high-frequency part of the comb disappears. At this point, the signal is severely degraded and fails to output the MFC signal properly.

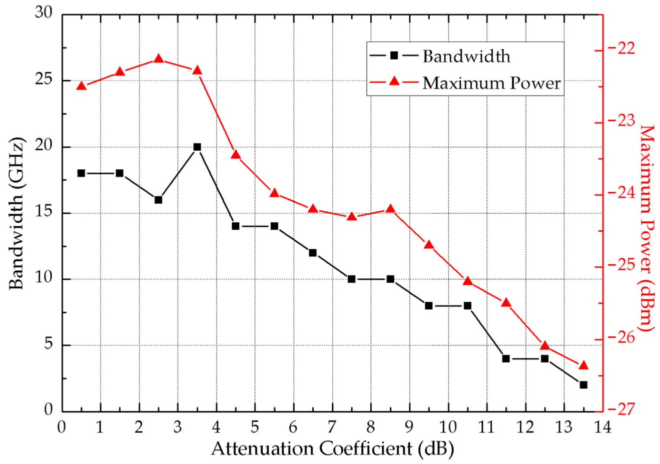


Figure 4. Effect of the attenuation coefficient on the bandwidth and maximum power of the MFCs. The X-axis is represented by the attenuation coefficient of VOA1.

Figure 4 illustrates a curve depicting the relationship between the attenuation coefficient and the bandwidth and maximum power of the MFC signal. It can be observed that the bandwidth and maximum power of the MFC signal reach their peak when the attenuation coefficient is around 3 dB, indicating the best output performance of the MFC. Setting the attenuation coefficient too high or too low will alter the injected optical power, leading to a decrease in both the MFC bandwidth and maximum power, thereby compromising the quality of the output MFC signal. It should be noted that changing the attenuation coefficient of VOA2 will have a similar impact on the system, although further details are not provided here. Based on the experimental results mentioned above, it is evident that the injected optical power significantly influences the output MFC. Therefore, it is essential to set the attenuation coefficient appropriately in practical applications.

3.3. Effect of Modulation Frequency and Amplitude on MFC

To validate the tunability of the comb spacing of the MFC, we conducted experiments to assess its output by varying modulation signal frequencies and amplitudes. During the experiment, the center wavelengths of SLA and SLB remained stable, and the attenuation coefficients of VOA1 and VOA2 were set to 3.5 dB and 5.5 dB, respectively. We maintained the amplitude of the modulation signal at 0.8 V while varying its frequency from 1 to 9 GHz. By observing the outputs through an electrical spectrum analyzer, MFC signals with different comb spacings were obtained. The MFC spectra for modulation signal frequencies of 2 GHz and 3 GHz are shown in Figure 5a,b, respectively.

By comparing Figure 5a,b, it is apparent that the comb line spacing of the output MFC signal can be controlled by adjusting the modulation signal frequency. Moreover, the power discrepancy between the high-frequency and low-frequency regions of the MFC signal is relatively small, resulting in minimal noise fluctuations. The relationship between the modulation signal frequency and the MFC signal bandwidth is shown in Figure 6. As the modulation frequency increases, the overall bandwidth of the MFC signal decreases, while the maximum output power of the MFC increases. This phenomenon occurs because as the RF signal frequency increases, the number of spectral sidebands in the output decreases, leading to a higher power allocation to each comb line after photoelectric conversion.

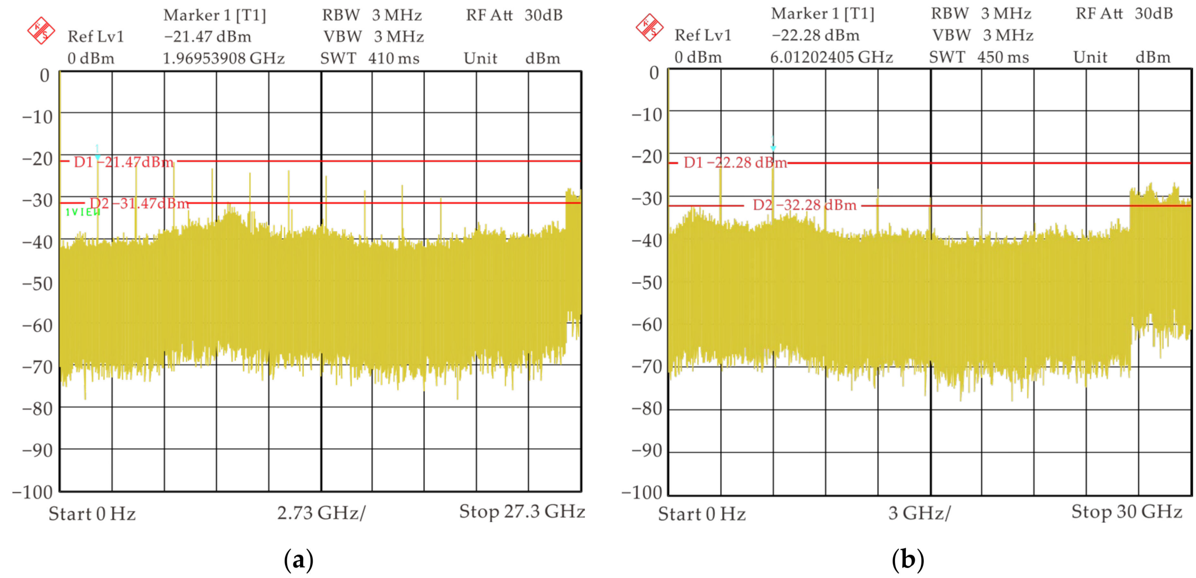


Figure 5. Electrical spectrum of the MFC when the modulation frequency is 2 GHz (**a**) and 3 GHz (**b**).

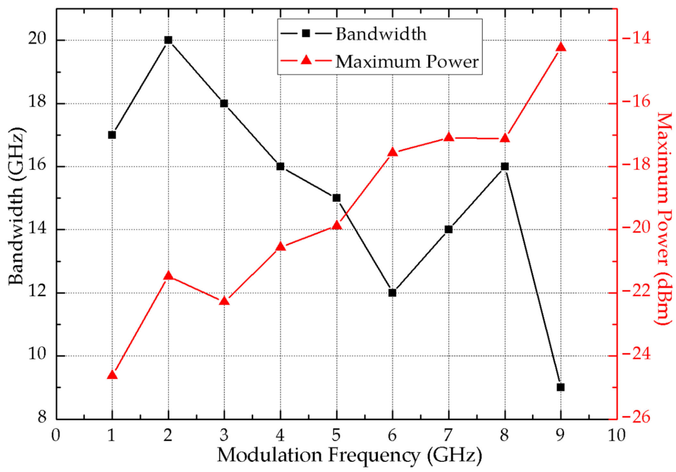


Figure 6. Effect of the modulation frequency on the bandwidth and maximum power of the MFCs.

Furthermore, the amplitude of the modulating signal also influences the bandwidth and power of the MFC signal. Experimental testing revealed that the flattest comb lines were achieved when the amplitude was set to 0.8 V. It can be obtained that increasing the amplitude of the modulating signal has a diminishing effect on the maximum power of the generated MFC signal. The MFC spectra for modulation signal amplitudes of 0.2 V and 0.8 V are presented in Figure 7a,b, respectively.

Based on these experimental findings, it can be concluded that the MFC comb spacing is solely controlled by the modulation signal frequency, making it easily adjustable. In practical applications, it is crucial to set the modulation signal amplitude appropriately to obtain high-quality MFC signals.

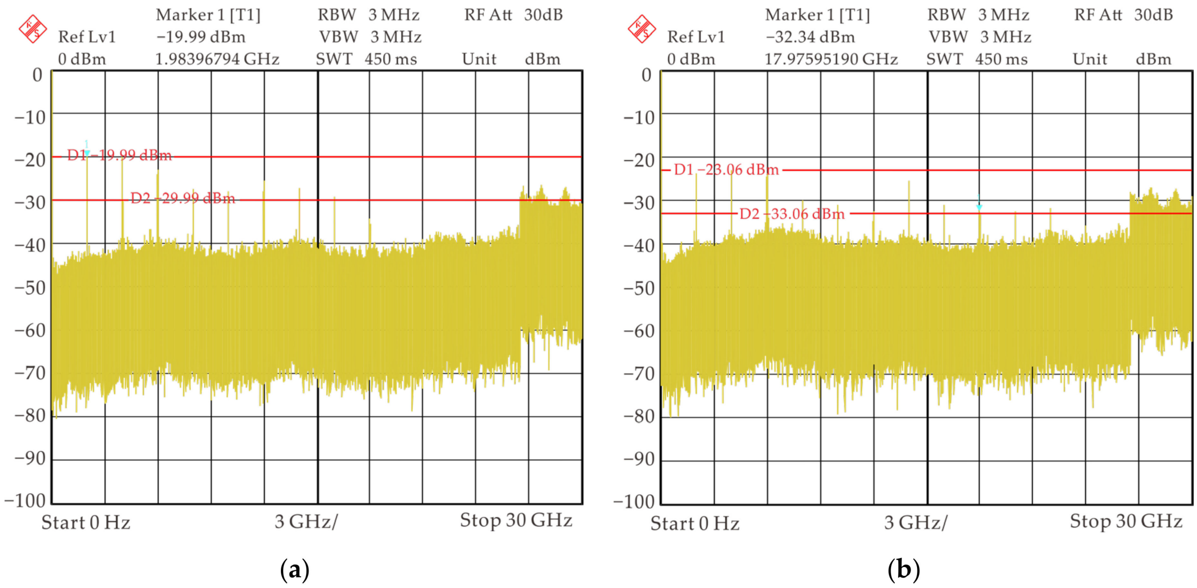
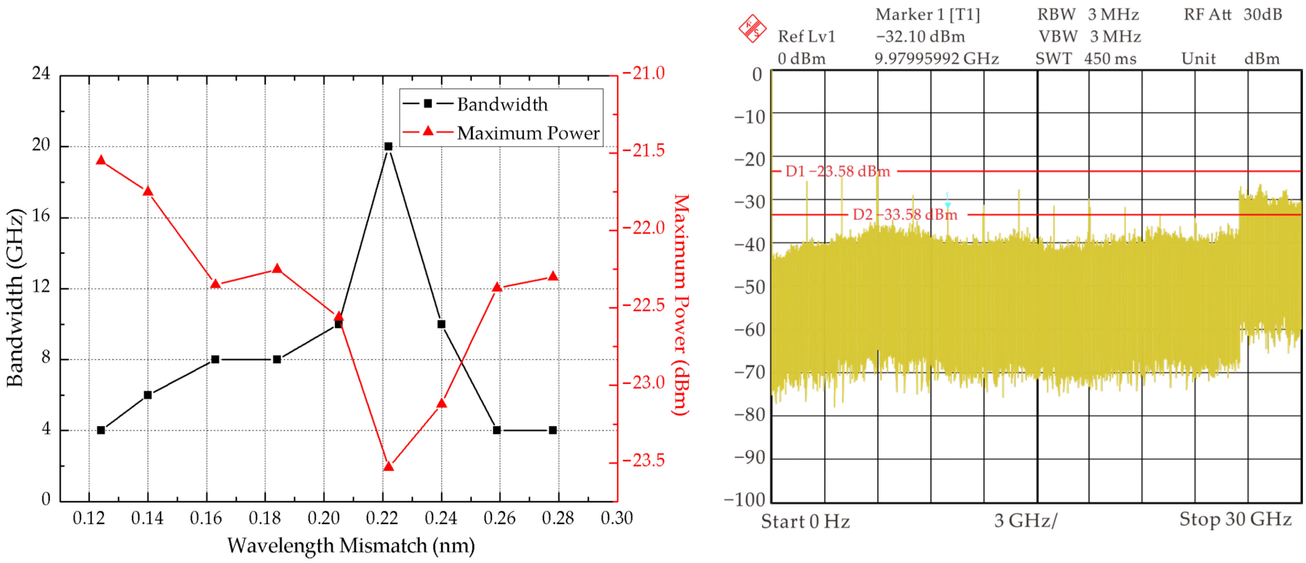


Figure 7. Electrical spectrum of the MFC when the modulation amplitude is 0.2 V (**a**) and 0.8 V (**b**).

3.4. Effect of Frequency Detuning on MFC

Frequency detuning is an important parameter for analyzing the nonlinear dynamics of semiconductor laser outputs, and it also affects the performance of MFCs in schemes based on optical mutual injection for generating microwave frequency combs. To investigate the effect of frequency detuning, while keeping the other experimental parameters constant, the center wavelength of the laser was controlled using a temperature controller, and the output optical power of the laser was regulated by a current source. In the experiment, the center wavelength of SLB was set to 1550.430 nm and the current was set to 35.86 mA. The wavelength detuning between SLA and SLB was controlled by adjusting the temperature of SLA to shift its center wavelength. The temperature controller was used to vary the SLA temperature within the range of 22.6 to 24.0 °C with a step size of 0.2 °C. The relationship between wavelength detuning and the MFC bandwidth and maximum power is shown in Figure 8a.

Based on Figure 8a, it is evident that when the temperature of SLA is 23.4 °C, this results in a center wavelength of 1549.652 nm and a wavelength detuning of 0.222 nm between the two lasers. The output MFC bandwidth reaches its peak value at 20 GHz with a maximum power of −23.58 dBm, and the electrical spectrum in the best condition is shown in Figure 8b. As the wavelength detuning increases or decreases gradually, the MFC bandwidth declines rapidly. This trend occurs for several reasons. When the wavelength detuning is too small, the optical frequency combs (OFCs) generated by the two lasers overlap significantly, leading to excessive power fluctuations in the beat frequency and substantial attenuation in the high-frequency region, ultimately causing a decrease in the bandwidth. On the other hand, when the wavelength detuning is too large, the distance between the two sub-OFCs becomes too great, resulting in reduced power at the intermediate frequency of the MFC after beating, leading to a significant decrease in the flatness. Therefore, adjusting the wavelength detuning in practical applications can effectively enhance the quality of the MFC signal. Moreover, compared with the unidirectional optical injection scheme, the stability requirement for the laser center wavelength is significantly reduced.



(**a**) (**b**)

Figure 8. Effect of frequency detuning on the bandwidth and maximum power of the MFCs (**a**) and electrical spectrum of the MFC when the wavelength detuning is 0.222 nm (**b**).

4. Discussion

In recent decades, MFC generation based on photoelectric approaches has been reported. For example, MFC signals with a bandwidth of 3 GHz have been generated using a sub-harmonic frequency-locked state produced by the opto-electric feedback of an SL [18]. However, the comb spacing of the MFC is not strictly equal and the noise of the non-comb components is obvious. An MFC signal with an amplitude of ±5 dB and a bandwidth of 20 GHz was generated by injecting regular optical pulses generated by opto-electric feedback from an SL into other SLs [19]. Nevertheless, the problem is that the signal is not stable and the comb line spacing is small. Alternatively, by exploiting the nonlinear effect of the STM tunnel junction, the generation of MFC signals up to 200 harmonics with a bandwidth close to 15 GHz was achieved, but the resulting MFC comb spacing was difficult to tune and had a large phase noise [5,6].

Therefore, in order to obtain ultra-wideband high-quality MFC signals with balanced power and uniformly tunable comb spacing, we propose a scheme for obtaining MFCs through mutual injection into the nonlinear dynamical state presented by SLs. Compared with the unidirectional injection scheme, this scheme achieves an enhanced MFC bandwidth and more balanced power, and partially reduces the system requirements for device stability and ambient temperature. However, it should be noted that this scheme possesses increased system complexity, and the MFC quality and system complexity should be weighed in practical applications. After determining the optimal operating parameters through experiments, devices such as PCs and VOAs can be removed and polarization-maintaining fibers and fixed optical attenuators can be used instead to simplify the system structure. In addition, the scheme proposed in this study can be applied to other SLs with more abundant characteristics, such as quantum well lasers and vertical-cavity surface-emitting lasers (VCSELs).

5. Conclusions

In this study, a scheme for generating tunable MFCs based on optical mutual injection is proposed. The experimental results demonstrated the generation of a broadband MFC signal with a bandwidth exceeding 20 GHz and relatively flat comb power. Through the designed experiments, the effects of injected optical power, modulation frequency and amplitude, and wavelength detuning on the generation of MFC signals were analyzed. It was confirmed that the MFC comb-line spacing can be tuned within the range of 1 to 9 GHz by adjusting the modulation frequency and selecting the appropriate operating parameters. When compared to the unidirectional optical injection method, the MFCs generated by this scheme exhibit several advantages, including a larger continuous bandwidth, lower phase noise, more balanced comb power, and easier adjustment of comb spacing. Furthermore, it has the ability to cover multiple frequency bands such as C, Ku, and Ka simultaneously, thus holding significant potential for broad application in fields such as satellite communication, radar guidance, and remote sensing detection.

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