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A Tunable Dual-Passband Microwave Photonic Filter Based on Optically Injected Distributed Feedback Semiconductor Lasers and Dual-Output Mach-Zehnder Modulator

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Abstract: In this paper, a novel approach to achieving a wideband tunable dual-passband microwave photonic filter (MPF) is proposed based on optical-injected distributed feedback (DFB) semiconductor lasers and a dual-output Mach–Zehnder modulator (DOMZM). The fundamental concepts for realizing the MPF are the wavelength-selective amplification effect and the period-one oscillation state under optically injected DFB lasers. These effects provide a widely tunable range of center frequency, along with high flexibility and low insertion loss. The proposed MPF is experimentally demonstrated, showing that the dual-passband center frequency in the MPF can be tuned independently from 19 to 37 GHz by adjusting the detuning frequency and injection ratio. Meanwhile, the insertion loss of the system is about 15 dB when there is no optical or electrical amplifier in the MPF link. The out-of-band suppression ratio of the MPF is more than 20 dB, which can be improved by adjusting the power of the two optical signals.

Keywords: microwave photonic filter; dual-passband filter; optically injected DFB laser; wavelength-selective amplification

1. Introduction

Microwave signal filtering plays an important role in microwave signal processing fields [1,2], such as wireless local area network (WLAN) communication, mobile communication and radar systems. Once inferior to traditional electrical microwave filters [3], filters based on photonic links have now come to be considered an effective solution for low transmission-loss, high-frequency, large-bandwidth microwave signal processing. Such solutions find applications in next-generation wireless networks, radar systems and electronic warfare systems.

Microwave photonic filters (MPFs) can typically be demonstrated using time-delay [4,5] and non-delay structures [6–8]. However, the MPFs realized by using time-delay structures are limited by the intrinsic periodic spectral response due to the finite impulse response, hindering their periodic tunability. In addition, they usually need single-mode optical fibers (G. 652) several kilometers

in length, or dispersion-compensating optical fibers of high dispersion coefficients, both of which make the structure of MPFs more highly multiplex. Numerous methods employing non-delay structures have been proposed and experimentally demonstrated in recent years, such as stimulated Brillouin scattering (SBS) [6], semiconductor optical amplifier [7] and phase-shifted fiber Bragg grating (PS-FBG) [8]. In [6], a high Q-factor MPF based on SBS was demonstrated, but the tuning range of the MPF was limited by the range of Brillouin frequency shift of low-tunability. In [7], an MPF based on a semiconductor optical amplifier with a frequency tuning range from 5 to 35 GHz was obtained, with a large 3-dB bandwidth around 4 GHz. In [8], the PS-FBG was used to implement conversion from phase-modulation to intensity-modulation (PM-IM), causing high insertion loss and low tunability of the passband bandwidth. Furthermore, dual-passband MPFs are indispensable and widely studied in different fields for a variety of practical applications, such as in multiband microwave systems like wireless and mobile communication, radar systems and satellite communication [9–12]. In [9], a switchable, tunable, dual-passband MPF based on a reflective-fiber Mach-Zehnder interferometer and dispersive medium was proposed, but was limited by the poor tunability of the time-delay structure. In [10], PM-IM conversion in two channels was implemented in order to obtain an MPF with two independently tunable passbands using a phase modulator (PM) and an equivalent phase-shifted fiber Bragg grating (EPS-FBG). However, the wavelength spacing of the two wavelengths in the proposed MPF was small, making center frequencies of the two passbands close and the frequency spacing tunability of the two passbands poor. In [11], a tunable dual-passband MPF based on a polarization modulator and a PS-FBG was demonstrated, but due to the influence of the nonlinear phase response of the PS-FBG, the sidelobes of the passband were high. In [12], a tunable and reconfigurable MPF based on photonic waveguide platform and SBS was proposed, which can adjust the shape of the MPF by electrically tailoring the SBS pump using an arbitrary waveform generator (AWG). The use of an AWG in the proposed MPF also realized multiple filters with varying center frequencies and bandwidth. However, the filter response was not ideal with a high passband ripple induced by the influence of the nonlinear effect, so it was necessary to use a feedback loop controlled by a computer to reduce the passband ripple in the system, which increased the complexity of the MPF.

In the present paper, we propose a new dual-passband MPF based on optical-injected distributed feedback (DFB) semiconductor lasers and a dual-output Mach-Zehnder modulator (DOMZM), with the merits of widely tunable range of center frequency, high flexibility and low insertion loss. In the proposed MPF, the microwave signals are applied to a DOMZM to achieve complementary intensity modulation. The respective optical signals are injected into the upper and lower slave DFB lasers by two optical circulators. Due to the influence of wavelength-selective amplification under the optically injected DFB lasers, the optical sidebands under the locking area are effectively amplified. Then, the dual-passband MPF is obtained by beating the optical carrier and amplified optical sidebands in a balanced photodetector (BPD). The center frequency of the MPF can then be tuned by adjusting the injection ratio and the detuning frequency. Furthermore, link noise can be reduced by the BPD's inherent nature of common-mode noise cancellation and the improvement of signal gain. The experimental results on the proposed MPF show that the center frequency of the dual-passband MPF can be tuned independently from 19 to 37 GHz. Meanwhile, the tunable range of the center frequency of the link is limited by the bandwidths of the modulator and photodetector. The MPF can work for a higher frequency by using a DOMZM and BPD with larger bandwidths. Furthermore, the insertion loss is about 15 dB without optical or electrical amplification, which is much lower than that for MPFs realized by other structures [8–11].

2. Operation Principle

A schematic diagram of the tunable dual-passband MPF is shown in Figure 1. The MPF link consists of a laser source, a dual-output Mach-Zehnder modulator (DOMZM), two polarization controllers (PCs), two optical circulators (CIRs), two DFB semiconductor lasers and a balanced photodetector (BPD). The performance of the MPF is evaluated using a vector network analyzer (VNA).

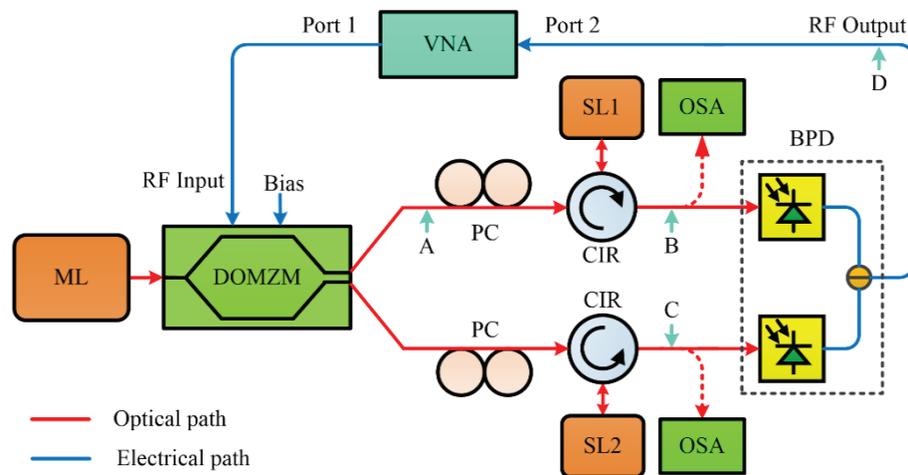


Figure 1. Schematic diagram of the tunable dual-passband microwave photonic filter (MPF). ML: master laser; SL: slave laser; DOMZM: dual-output Mach–Zehnder modulator; CIR: optical circulator; PC: polarization controller; BPD: balanced photodetector; VNA: vector network analyzer; OSA: optical spectrum analyzer.

As shown in Figure 1, a tunable laser source (TLS) is used as a master laser (ML), two DFB lasers are used as slave lasers (SLs) and the DOMZM is set at quadrature bias point in the proposed structure. The microwave signals modulate optical signal in the DOMZM and the high order sidebands (≥ 2) can be ignored where only ± 1 st sidebands are considered under small signal modulation conditions. So, the microwave signals are applied to the light wave from the ML with the frequency f_m . Two modulated optical signals with equal intensities are obtained via complementary intensity modulations at the output of DOMZM, and two modulated optical signals are then individually injected into the SLs DFB1 and DFB2 through CIRs to realize optical injection. The PCs in the link are used to adjust the polarization between the ML and SLs to maximize the injection efficiency. Finally, the optical signals from the SLs are coupled into the BPD.

The principle of the dual-passband MPF is shown in Figure 2, where f_0, f_1, f_2, f_3 and f_4 are the frequencies of the microwave signals to be processed. The free-running frequencies of DFB1 and DFB2 are f_{s1} and f_{s2} . However, f_{s1} is different from f_{s2} in our structure. As shown in Figure 2a, when the optical carrier is modulated by microwave signals, -1 st sidebands of the modulated optical signals are generated with the frequencies of $f_m - f_0, f_m - f_1, f_m - f_2, f_m - f_3$ and $f_m - f_4$. When the modulated optical signals are sent to the slave laser, the cavity mode of the slave DFB laser is red-shifted due to the change in carrier concentration based on the effect of the optical injection [13], and an optical gain spectrum centered at the red-shifted cavity mode with frequency f_{cav} will be produced. When the sidebands of modulated optical signals fall into the range of the gain spectrum, the optical signals will be selected and amplified. After beating in the BPD, signals of interest are selected and an MPF can be realized at the output of the BPD.

The center frequency of the passband can be set by adjusting the detuning frequency and the injected ratio individually or together. In the proposed approach, the frequencies of the optical gain spectrum of two DFB lasers are f_{cav1} and f_{cav2} , respectively. The modulated signals with small sideband amplitudes falling into the range of the optical gain spectrum are amplified depending on the detuning frequency. The amplitude of the other sideband signals remains unchanged. Finally, two microwave signals with different frequencies are generated at the output of the BPD by beating the amplified optical component with the optical carrier, and other microwave signals are suppressed, realizing the dual-passband microwave photonic filtering.

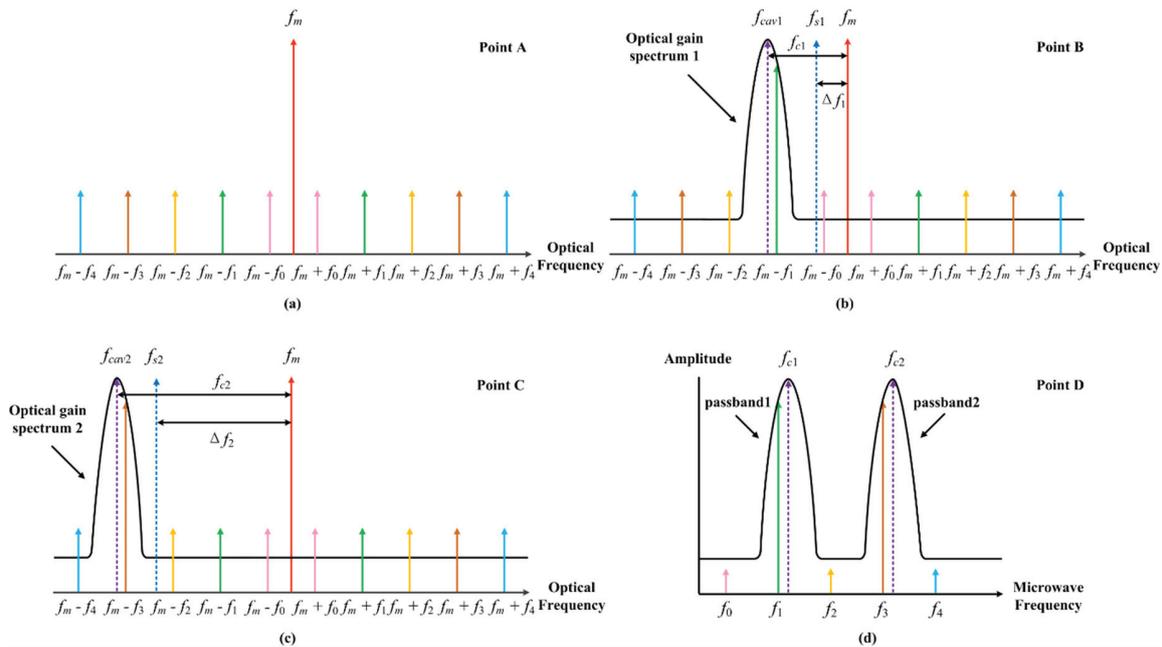


Figure 2. Principle of the tunable dual-passband MPF. (a) is the optical spectrum at point A; (b) is the optical spectrum at point B; (c) is the optical spectrum at point C; (d) is the electrical spectrum at point D after the signals’ beating in BPD.

Assuming that optical carrier is modulated in DOMZM by microwave signals with different frequencies, one of the microwave signals can be expressed as:

$$V(t) = V_{DC} + V_0 \cos(2\pi f_0 t) \tag{1}$$

where V_{DC} is the bias voltage applied to the DOMZM, V_0 is the amplitude of the microwave signal and f_0 is the frequency of the microwave signal. The DOMZM is set at quadrature bias point by using a modulator bias controller. The output optical fields of the DOMZM, under a condition of small signal modulation, can be written as:

$$E_{DOMZM}(t) = \frac{1}{2} E_m \exp(j \cdot 2\pi f_m t) \left[\exp\left(j \frac{\pi V(t)}{2V_\pi}\right) + j \exp\left(-j \frac{\pi V(t)}{2V_\pi}\right) \right] \tag{2}$$

where E_m is the amplitude of the input optical signal of the DOMZM and f_m is the frequency of the output optical signal of the ML. V_π is the half-wave voltage of the DOMZM. Then, Equation (2) can be expanded with Bessel functions:

$$E_{DOMZM}(t) \approx \frac{\sqrt{2}}{2} E_m \left\{ J_0(\beta_1) \exp\left(j\left(2\pi f_m t + \frac{\pi}{4}\right)\right) + J_1(\beta_1) \exp\left[j\left(2\pi(f_m + f_0)t + \frac{\pi}{4}\right)\right] + J_1(\beta_1) \exp\left[j\left(2\pi(f_m - f_0)t + \frac{\pi}{4}\right)\right] \right\} \tag{3}$$

where $\beta_1 = \pi V_0 / 2V_\pi$. $J_0(\beta_1)$ is the zero-order Bessel functions of the first kind. $J_1(\beta_1)$ is the first-order Bessel functions of the first kind. According to Equation (3), $f_m - f_0, f_m - f_1, f_m - f_2, f_m - f_3$ and $f_m - f_4$ are the frequencies of -1 st sidebands of the modulated signals, as shown in Figure 2a.

As far as is known, if the detuning frequency is written as $\Delta f = f_m - f_s$ and the range of the optical gain spectrum is changed with Δf , then a dual-passband MPF with a tunable center frequency can be obtained. The frequency f_{cav} of the red-shifted cavity mode of the DFB can be expressed as [14,15]:

$$f_{cav} = f_s + \frac{1}{4\pi} \alpha g(N - N_{th}) \tag{4}$$

where α is the linewidth enhancement factor, g is the linear gain coefficient, N is the carrier number in the cavity, and N_{th} is the threshold carrier number. The -1 st sidebands of the modulated signals, which fall into the gain spectra with center frequencies f_{cav1} and f_{cav2} will be selected and amplified after optically injected DFB lasers which are shown in Figure 2b,c. A dual-passband MPF will be realized after the signals' beating in BPD, which can be seen in Figure 2d.

Furthermore, the resonance frequency f_{res} between the ML and the red-shifted cavity mode of the DFB can be expressed as:

$$f_{res} = f_m - f_{cav} \quad (5)$$

Combining Equations (4) and (5) with the detuning frequency yields the following equation:

$$f_{res} = \Delta f - \frac{1}{4\pi} \alpha g (N - N_{th}) \quad (6)$$

Considering the principle of the MPF, the center frequencies f_c of the two passbands in the MPF are equal to the resonance frequencies of DFB1 and DFB2, which can be expressed as:

$$f_c = \Delta f - \frac{1}{4\pi} \alpha g (N - N_{th}) \quad (7)$$

It should be noted that N is a parameter that is not only interrelated with the detuning frequency Δf , but is also related to the injection ratio (R), which is defined as the square root of the ratio between the power of the injected light and the power of free-running slave DFB lasers [13]. The power of the injected light is controlled by tuning the power of the optical signal output from the ML when the polarization of the injected light is fixed in the MPF link. The frequency and power of the free-running DFB laser can be controlled by tuning the temperature controller and laser diode controller of the DFB laser driver in the experiment. With the change in detuning frequency or injection ratio, the center frequency of the optical gain spectrum will be changed at the same time. So, in the proposed MPF, both the center frequencies of the two passbands can be changed by adjusting the injected ratio R and detuning frequency Δf , individually or together, with wide tunability.

3. Experiment and Results

An experiment based on the proposed dual-passband MPF configuration shown in Figure 1 was performed to verify the effectiveness of the approach. In the experiment, a TLS (NKT E15) was used as an ML with a CW optical power up to 16 dBm and then the CW light was sent to a DOMZM (EOSPACE). The DOMZM was set at quadrature bias point. A VNA (Keysight N5227B) was used to measure the frequency response of the MPF. The output power of the VNA was -10 dBm, with a frequency range of 1 to 45 GHz. The microwave signals to be tested were applied to the DOMZM from port 1, complementary intensity modulation is obtained at the two DOMZM outputs. So that two modulated signals with equal intensities could be obtained at the output of the DOMZM. Then the signals were injected into the SLs through PCs and CIRs. The PC was used to adjust the polarization state of the optical signals between the ML and the SL so that the maximum injection efficiency could be achieved in the experiment. Finally, a BPD (U2T) was used to realize the optical-to-electrical conversion and eliminate the common-mode noise of the MPF link. An optical spectrum analyzer (OSA) was used to analyze the optical spectrum after injection before the optical signals' beating in the BPD.

As can be seen from Equation (4), the center frequency of the two passbands could be controlled by changing the parameter N which can be tuned by adjusting the detuning frequency Δf and injected ratio R , individually or together. The influence of the detuning frequency was first demonstrated. In the experiment, the output power of the ML was set as 11.76 dBm with a wavelength of 1548.928 nm. The free-running wavelength of the SL1 was tuned from 1548.936 to 1549.128 nm, which can be controlled by tuning the temperature controller of the DFB laser driver. The free-running wavelengths of SL1 and SL2 were different. The detuning frequency Δf_1 between the ML and SL1 was tuned

from 1 to 25 GHz. Meanwhile, the detuning frequency Δf_2 between the ML and SL2 was fixed, and the free-running power of two different SLs was also fixed. As shown in Figure 3, when the detuning frequency Δf_1 was changed from 1 to 25 GHz, the central response frequency of the first passband could be tuned from 20.71 to 30.83 GHz based on the influence of the wavelength-selective amplification and the period-one (P1) oscillation state [13] under the optically injected DFB lasers. At the same time, the out-of-band suppression ratio of the MPF can be obtained from the Z-axis in Figure 3. The out-of-band suppression ratio of the first passband was around 20.9 dB, and the central response frequency of the second passband was fixed at 33.98 GHz with the out-of-band suppression ratio around 21.3 dB. However, the 3-dB bandwidths of the two passbands in our MPF were about 0.85 and 0.95 GHz, which were limited by the locking amplification area bandwidth under optical injection and the linewidth of the DFB lasers.

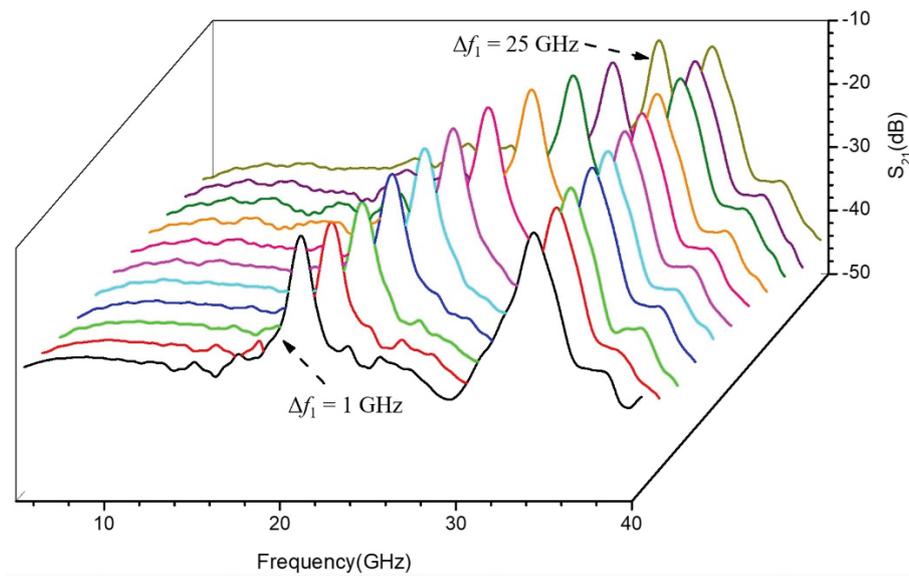


Figure 3. Results of the tunability of passband 1 by adjusting the detuning frequency Δf_1 from 1 to 25 GHz.

Then the optical wavelengths of the ML and SL1 were different fixed, and the output optical powers of all three lasers were also fixed. The free-running wavelengths of SL1 and SL2 were different. The detuning frequency Δf_2 could be continuously tuned by changing the free-running wavelength of the SL2 from 1549.605 to 1549.725 nm, which can be controlled by tuning the temperature controller of the DFB laser driver when the wavelength of ML was fixed at 1549.520 nm with a simultaneous stable detuning frequency Δf_1 . Therefore, the central response frequency of the first passband could be fixed at 19.13 GHz with the out-of-band suppression ratio around 26.2 dB, and the center frequency of the second passband could be tuned from 24.75 to 32.41 GHz with the out-of-band suppression ratio around 28.8 dB, as shown in Figure 4. The 3-dB bandwidth of the first passband was about 0.5 GHz, and the 3-dB bandwidth of the second passband was about 0.6 GHz. On the other hand, the tuning of the response frequency was nonlinear with the simultaneous alteration of Δf , which resulted from the influence of the P1 oscillation state under the optically injected DFB lasers.

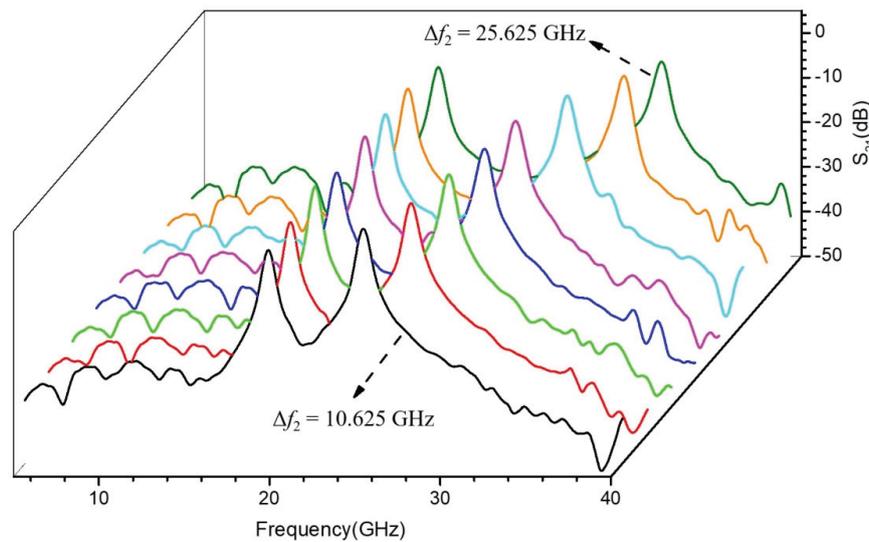


Figure 4. Results of the tunability of passband 2 by adjusting the detuning frequency Δf_2 .

According to the theory, we found that the central response frequency of the MPF could also be tuned by tuning the injection ratio R , which could be defined as the square ratio between the power of the injected optical signal and the power of the free-running SL. In the experiment, the free-running powers of the SL1 and SL2 were fixed at 8.95 and 9.3 dBm when the wavelength of the ML was fixed at 1548.928 nm, and the free-running wavelengths of the two SLs were also different and fixed. The injection ratio R could be adjusted when the power of the ML was tuned from 10 to 13.42 dBm. As shown in Figure 5, when the injection ratio R was altered, the center frequency of the first passband could be tuned from 22.73 to 26.91 GHz with a 3-dB bandwidth of 0.8 GHz. At the same time, the center frequency of the second passband could be tuned from 30.56 to 36.91 GHz, with a 3-dB bandwidth of 1.1 GHz. The experimental results show that the tunability of the MPF could be produced by tuning the injection ratio R . Furthermore, the results of the central response frequencies of two passbands in the MPF are limited by the bandwidth of the modulator and photodetector used in the experiment. Therefore, a higher tunable passband frequency bandwidth and center frequency of the passband could be achieved by employing a DOMZM and BPD with higher bandwidths.

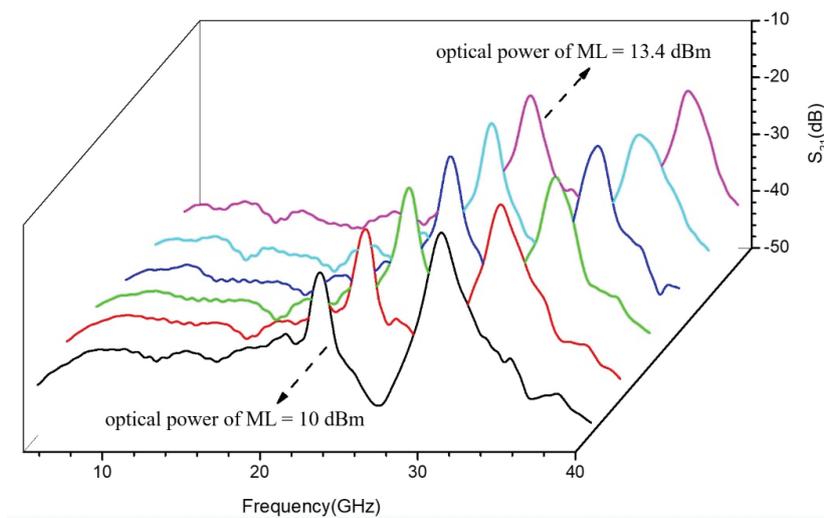


Figure 5. Results of the tunability of the dual-passband MPF by adjusting the optical power of ML from 10 to 13.4 dBm.

Due to the influence of the variations between the two SLs, there was a difference in the optical power of the two links before beating in the BPD. Therefore, the out-of-band suppression ratios of the MPF were not identical in the two cases. The injection ratio R and the detuning frequency Δf were tuned to create a power balance with the same phase between the two links before beating in BPD. The signals which were out of the passband could be suppressed based on the balanced differential detection of the BPD, so that the out-of-band suppression ratio were further improved. As shown in Figure 6, when the optical power of the first MPF was similar or equal to the second, the maximum out-of-band suppression ratio of dual-passband MPF could be increased by 23.2 dB.

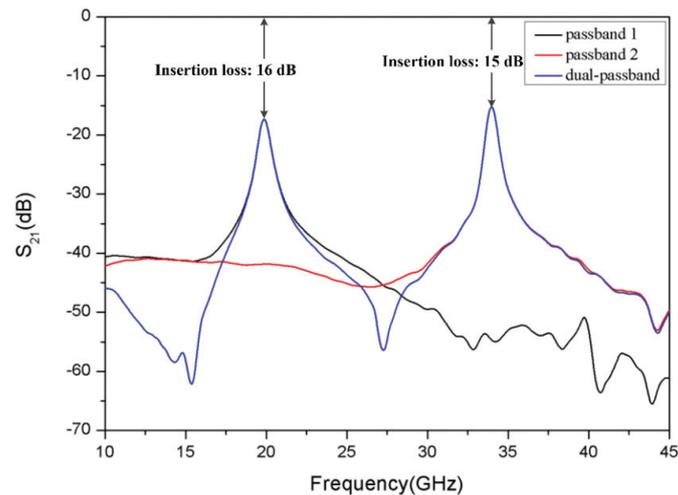


Figure 6. Results of the improved out-of-band suppression ratio by adjusting the power and phase of two links.

On the basis of the results shown in Figure 6, a tunable dual-passband MPF with a higher out-of-band suppression ratio of more than 30 dB could be created by tuning Δf , as shown in Figure 7. Finally, with the effect of optical-injected DFB lasers, the insertion loss of our MPF, which was defined as the difference between the signals' power after filtering at the input of the VNA and the signals' power at the output of the VNA, was only about 15 dB without any optical or electrical amplifier, which was much lower than most MPFs created by other structures [8–11].

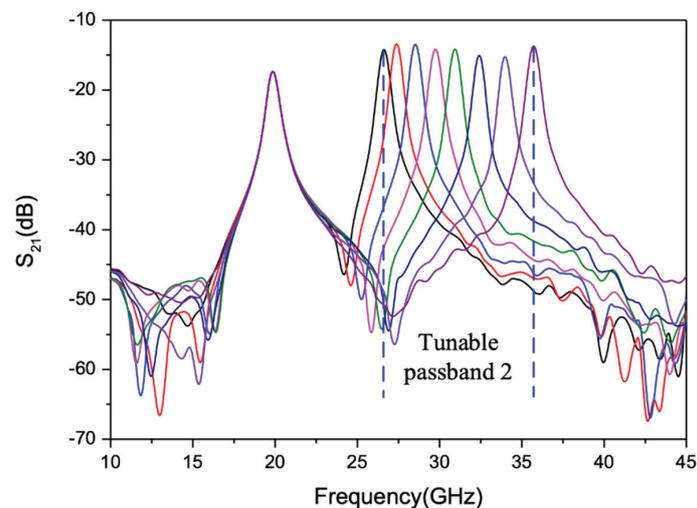


Figure 7. Results of a tunable dual-passband MPF with a high out-of-band suppression ratio.

4. Conclusions

In this paper, a novel approach to creating a tunable dual-passband MPF based on the influence of wavelength-selective amplification and the P1 oscillation state under an optically injected DFB semiconductor laser was proposed and experimentally demonstrated. The experimental results show that the central response frequency of the passband in the MPF could be widely tuned up to 36.91 GHz by adjusting the detuning frequency Δf and the injection ratio R . At the same time, the center frequencies of the two passbands were only limited by the bandwidths of the modulator and photodetector, and the tunable range of the passbands could be further adjusted by using a DOMZM and BPD with larger bandwidths. The experimental results show that the out-of-band suppression of the MPF was more than 20 dB. Furthermore, adjusting the injected ratio R and detuning frequency Δf to balance the optical power of two single-passband MPFs produced a dual-passband MPF with a maximum out-of-band suppression ratio increased by 23.2 dB. Meanwhile, the insertion loss was only about 15 dB, which is much lower than many other dual-passband MPFs.

Author Contributions: J.Z. designed and set up the experiment; P.D., R.Y. and R.L. carried out the measurements under the supervision of J.H., M.Z. and Y.G. provided the theoretical support for modelling the experiment. J.Z. wrote the manuscript and all authors suggested improvements. All authors have read and agreed to the published version of the manuscript.

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