High-speed Switchable Dual-passband Microwave Photonic Filter with Dual-Beam Injection in an SMFP-LD

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***Abstract*— In this paper, a high-speed switchable dual-passband microwave photonic filter (MPF) using a single mode Fabry-Perot laser diode (SMFP-LD) is proposed and experimentally demonstrated. Benefiting from the wavelength selective amplification in the SMFP-LD, the +1st sideband of two external beams injected after phase modulation can be amplified in the gain spectrum of the SMFP-LD. Hence, an MPF with two tunable passbands is generated. The switching of the generated passbands is obtained through the switching signal of 1 Gbps applied to the modulator, which controls the power of one of the external beams. By properly setting the external beams' injection parameters, the passbands of MPF can switch from single passband to no passband, single passband to dual passband, and one passband to another passband. In this experiment, the maximum center frequency and tuning range of the passbands is 45.0 GHz and 35.0 GHz, respectively. The out-of-band rejection ratio and 3 dB bandwidth of the proposed filter are 29.62 dB and 83 MHz, respectively.**

***Index Terms*—optical injection, SMFP-LD, microwave photonic filters, switch**

I. INTRODUCTION

MICROWAVE filter is one of the crucial components in many fields, such as radar system, Radio-over-Fiber system, which selects the required signal of different center frequency and bandwidths, suppresses the interference, and effectively reduces the dynamic range requirement of the systems [1-3]. However, the electric domain filter's performance is limited by many factors, such as low center frequency and bandwidth, limited tunability, and electromagnetic interference. In recent years, microwave photonic filter (MPF) has been proposed to overcome the limitations of the electrical microwave filter. The main principle of MPF is converting RF signal to an optical domain and then sent to an optical subsystem for signal processing. MPF has the same function as traditional electrical microwave filters but has better filtering performance [4-6]. Benefiting from the flexible optical subsystem, the MPF with high Q value, tunable passband, high center frequency, and flexible reconfigurability can be realized.

One commonly used method for implementing MPF is by weighting, delay, and a sum of optical signals in multiple taps, divided into finite impulse response (FIR) filters [7, 8] and infinite impulse response (IIR) filters [9, 10] according to the numbers of taps. However, an intrinsic periodic frequency response of these MPFs restricts the processing signals to be a fraction of the free spectral range to avoid spectral overlapping. In addition, the tunability of the passband in these MPFs is poor due to the difficulty in tuning the time delay difference between taps. Hence, many schemes have been proposed to generate MPFs with a single passband or multi-passband. Among them, one is based on a sliced broadband optical source and a dispersive medium, such as a fiber Mach-Zehnder interferometer (FMZI) and a standard single mode fiber [11, 12]. In this method, the free spectrum range is infinite in theory; hence, it has a frequency response of a single passband. It can be modified to obtain a multi-passband by introducing a multi-path FMZI or multi-dispersive medium. Another method to generate an MPF with a single passband is based on one phase modulator and a narrow-band phase-shifted fiber Bragg grating (PS-FBG) by converting phase modulation into intensity modulation [13, 14]. However, the MPF structures mentioned above lack center frequency tunability, are complex in configuration and are sensitive to external environmental disturbances, such as temperature and vibration. Recently, semiconductor lasers and semiconductor optical amplifiers are used to demonstrate optical filters in many systems [15-19]. The fundamental principle of these methods is based on the wavelength-selective amplification of the semiconductor laser. Optical injection to a semiconductor laser has been proposed to generate an MPF with single or multi-passband, which has a wide tunable frequency range, simple structure, and good center frequency reconfigurability. However, with the increasing complexity of signal processing, there is an urgent need for a filter with programmable and switchable passbands, which can be applied in multi-band, multifunctional systems, such as frequency-hopping radar and the secure communication system.

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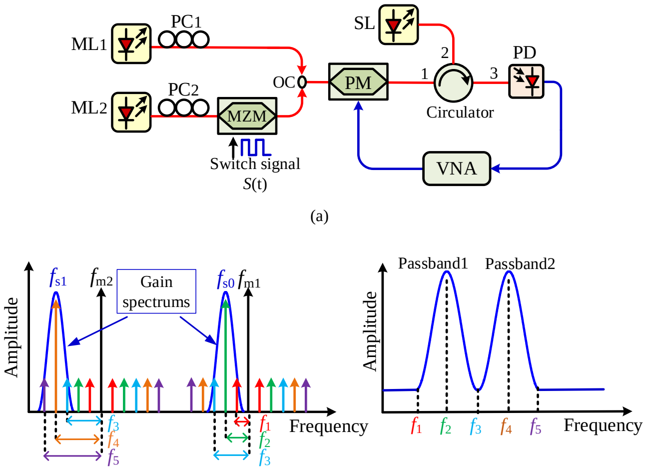
The MPFs mentioned above can not realize the function of programmable and switchable passbands.

In this paper, an MPF with high-speed switchable passbands is proposed and experimentally demonstrated. The proposed scheme is based on dual-beam injection to a single mode Fabry-Perot laser diode (SMFP-LD). Two external beams after phase modulation are injected into two modes of the SMFP-LD with positive frequency detunings. Benefiting from the wavelength selective amplification effect of the modes in the SMFP-LD, the $+1^{st}$ sidebands of two external beams after phase modulation are amplified in the laser cavity of the SMFP-LD. Hence, a dual-passband MPF is generated by optically beating the injected beam and the corresponding amplified $+1^{st}$ sideband. In addition, a switching signal of 1 Gbps is used to control the power of one of the external beams. With a proper setting of the optical injection parameters of two external beams, the proposed MPF can switch its passbands from a single passband to no passband; one passband to another passband; and single passband to two passbands. The demonstrated dual-passbands have a maximum center frequency and tuning range of 45.0 GHz and 35.0 GHz, respectively. Also, the proposed scheme shows a better response in its out-of-band suppression ratio and 3 dB bandwidth of dual-passbands MPF, which are measured as 29.62 dB with a 3 dB bandwidth of 85 MHz, respectively. Hence, the proposed MPF scheme is suitable for different applications, including microwave photonics, as it possesses simple configuration, good reconfigurability, low cost, compact, and integratable features.

II. EXPERIMENT SETUP AND PRINCIPLE

The experimental setup of the proposed MPF with high-speed switchable passbands subjected to dual-beam injection into an SMFP-LD is shown in Fig. 1(a). The SMFP-LD used in the experiment is a specially designed FP-LD, which comprises a commercial multi-mode FP-LD with a multi-quantum well of 300 µm and a built-in external cavity length of 4 mm. The external cavity is formed by eliminating the 6^{o} to 8^{o} inclination of the coupling fiber present in a commercial FP-LD. Due to the external cavity, a mode matching between the FP cavity and the external cavity can be obtained by varying the operating temperature. As a result, only one mode is dominant, suppressing all side modes. The side modes are with a high side mode suppression ratio due to the cursor effect of the internal and external cavities. By varying the operating temperature, a tuning of the dominant mode of 10 nm is obtained in an SMFP-LD [20]. Two tunable beams from master lasers (MLs, Agilent N7714A) are optically injected into a slave laser (SL, SMFP-LD) through polarization controllers (PCs) and a phase modulator (PM, EOSPACE, AZ-DV5-40-PFU-SFU-LV). The polarizers are used to maintain the TE mode of the injected beam and to obtain maximum gain through the modulators. The optical beam's power from ML2 is controlled by a switching signal applied to a Mach-Zehnder Modulator (MZM, 10 Gb/s, Lucent 2623NA). After an optical injection, the SL output is sent to a photoelectric detector (PD, XPDV2120RA-VF-FP) with a 3-dB bandwidth of 40 GHz for photo-to-electric conversion. A vector network analyzer (VNA, Keysight, PNA-L N5235A) is used to analyze the amplitude-frequency response of the proposed MPF. The basic principle of the proposed MPF with dual-passband is shown in Fig.1 (b) and (c). In Fig.1(b), the blue lines represent the gain spectrums of SL, and the black lines represent two external beams from MLs with frequencies of f_{m1} and f_{m2}. f_{m1} and f_{m2} are injected into two modes (f_{s0} and f_{s1}) of SL with positive frequency detuning. The injected beams are simultaneously phase modulated with a frequency-swept modulating signal generated by the VNA; thus, $\pm 1^{st}$ sidebands of f_{m1} and f_{m2} are generated. On increasing the modulating signal from f_1 to f_3, the $+1^{st}$ sideband of f_{m1} matches the corresponding mode's gain spectrum (f_{s0}) in the SL, whereas -1^{st} sideband of f_{m1} and sidebands of f_{m2} are out of the gain spectrum. Further increasing the modulating frequency from f_3 to f_5, only $+1^{st}$ sideband of f_{m2} is amplified by the gain spectrum, f_{s1}.



(a)

(b) (c)

Fig. 1 Illustration of the proposed high-speed switchable MPF (a) basic block diagram, (b) injection of two modulated beams into an SMFP-LD (c) filter response.

In both cases, whether the +1 sideband of f_{m1} or f_{m2} is in the gain profile when the $+1^{st}$ sideband matches the gain spectrum's center frequency, it attains the maximum gain. Figure 1(c) shows the frequency response of the optical spectrum corresponding to that in Fig. 1(b), which is generated by optical beating the injected beam and the corresponding amplified $+1^{st}$ sideband. A dual-passband response can be obtained with two-beam injections into different modes of SMFP-LD, as shown in Fig. 1(c). Passband 1 is generated by optical beating the injected beam f_{m1} and its amplified $+1^{st}$ sideband, and Passband 2 is generated by optical beating the injected beam f_{m2} and its amplified $+1^{st}$ sideband. The center frequency of the passbands is equal to the frequency detuning of the injected beam and the corresponding $+1^{st}$ sideband with maximum optical power.

For realizing the switching function of two passbands in the proposed MPF system, an MZM with a switch signal generated by AWG is used to switch the optical power of f_{m2}, as shown in Fig. 1(a). The principle of the switchable passbands MPF is shown in Fig. 2. Figure 2(a) shows the schematic optical spectrum of SMFP-LD with two injected beams. In Fig. 2(a-i), the blue line represents the optical spectrum of SMFP-LD, which has a dominant mode of f_{s0}. Two external injected beams with frequencies f_{m1} and f_{m2} are injected into the dominant mode, f_{s0} and the first side mode, f_{s1}, of the SMFP-LD with different positive frequency detunings. By controlling the optical power of f_{m1} and f_{m2}, the side mode, f_{s1}, is motivated to oscillate in the

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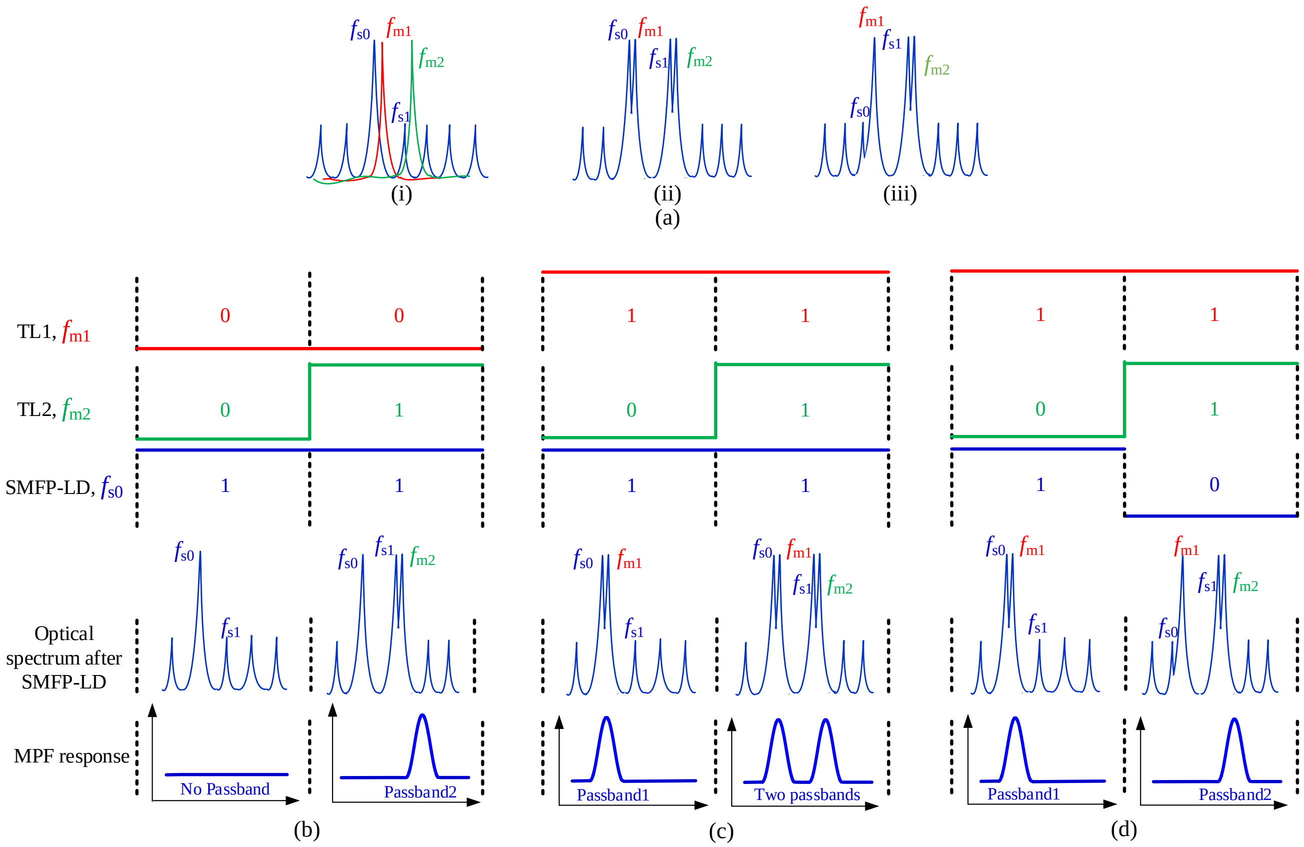

Fig. 2 Schematic spectrum diagram of the proposed MPF: (a) basic of dual-beam injection into an SMFP-LD, (b) no passband to single passband, (c) single passband to dual-passband, and (d) passband1 to passband2.

laser cavity, as shown in Fig. 2(a-ii), which is referred to as weak injection [21]. It is noted that in this case, the dominant mode f_{s0} is also present. However, on increasing the power of f_{m2}, the dominant mode, f_{s0} is suppressed, as shown in Fig. 2(a-iii), called strong injection. Figure 2(a) illustrates that by setting suitable parameters of two injected beams, the side mode, f_{s1}, can be motivated for the oscillation. Also, the suppression of the dominant mode, f_{s0}, can be controlled with the change in the injected beam parameters. A detailed analysis of the different mechanisms in SMFP-LD and semiconductor lasers with multi-beam injection can be found in previous research works [22, 23].

Figure 2(b)-(d) illustrates the switching function obtained by controlling the optical power of f_{m2} and, hence, obtaining the MPF with switchable passbands. In Fig. 2(b), the injected beam, f_{m1} is turned OFF, and f_{m2} is turned either ON or OFF. The “0” and “1” in Fig. 2 refer to the ON and OFF state of the optical power. When f_{m2} is “0”, only the dominant mode exists in the laser cavity. Hence, the MPF system has no filtering response. But when f_{m2} is “1”, the first side mode of the SMFP-LD is motivated to oscillate. Hence, a single passband (Passband2) can be generated in the MPF response, where the center frequency of the passband is equal to the frequency detuning of f_{s1} and f_{m2}. In Fig. 2(c), f_{m1} and f_{m2} are simultaneously injected into the SMFP-LD with weak injection, where f_{m1} is kept as “1,” and f_{m2} is switched from “0” to “1”. Hence, from the optical spectrum of the SMFP-LD after optical injection, we observe that the passband response of the generated MPF is switched from one passband (Passband1) to two passbands (Passband1 and 2). In Fig. 2(d), the SMFP-LD is injected by f_{m1} and f_{m2} under a strong injection state, where f_{m1} is kept as “1,” and f_{m2} is switched from “0” to “1”. When f_{m2} is “0”, only f_{s0} and f_{m1} exist in the laser cavity. Hence the MPF shows a single passband response, which is Passband1. But when f_{m2} is “1”, due to the strong injection, the dominant mode of the SMFP-LD is suppressed. As a result, only passband 2 is present and shows the switching of Passband1 to Passband 2. Hence, an MPF with switchable two passbands MPF can be generated using two beams injection to an SMFP-LD with suitable injection parameters.

III. EXPERIMENTAL RESULTS

A. *Generation of an MPF with single and two passbands*

At first, we analyze the generation of the proposed MPF scheme with single and two passbands. For this, the SMFP-LD is operated with the biasing current and operating temperature of 25 mA and 23 °C, respectively. With this biasing condition, the SMFP-LD has a dominant mode, f_{s0}, at the wavelength of 1545.91 nm. The external beam from ML1 with a wavelength of 1546.05 nm is injected into the dominant mode of the SMFP-LD. The output of SMFP-LD with ML1 injection is shown in Fig. 3(a). A frequency-swept signal from 0 to 50 GHz generated by the VNA is used for the phase modulation on f_{m1}, where the power of the modulating signal is set as -5 dBm. When the $+1^{st}$ sideband of the ML1 is within the dominant mode’s gain spectrum, the $+1^{st}$ sideband experiences the amplification; thus, an MPF response with a single passband, Passband1, is obtained by optical beating the f_{m1} and its amplified $+1^{st}$ sideband. The center frequency of the passband is 17.1 GHz,

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equal to the frequency detuning of the injected beam and the dominant mode, as shown in Fig. 3(b). Next, we change the injected beam from f_{m1} to f_{m2} with a wavelength of 1546.96 nm, injected to the first side mode of the SMFP-LD. In this situation, the dominant mode, f_{s0}, is suppressed, and the first side mode is motivated to oscillate in the laser cavity of the SMFP-LD. Hence, the gain spectrum of the SMFP-LD is changed to that illustrated in Fig. 3(c). Fig. 3(d) shows the corresponding frequency response of the MPF, which shows a single passband, Passband2, response with a center frequency of 29.5 GHz. On simultaneous injection of f_{m1} and f_{m2} to the SMFP-LD, both the dominant mode and the first side mode of the SMFP-LD are simultaneously motivated to oscillate, and hence, the gain spectrum of the SMFP-LD has two gain modes as shown in Fig. 3(e). The measured frequency response is shown in Fig. 3(f) with two passbands, and the center frequency is respectively equal to that in Fig. 3(b) and Fig. 3(d). The 3 dB bandwidth of Passband1 and Passband2 is 85 MHz and 180 MHz, respectively. Whereas the out-of-band rejection ratio of Passband1 and Passband2 is respectively 29.62 dB and 28.59 dB. Figure 3 confirms that the proposed MPF scheme has the capability of band-pass filtering with one or two passbands.

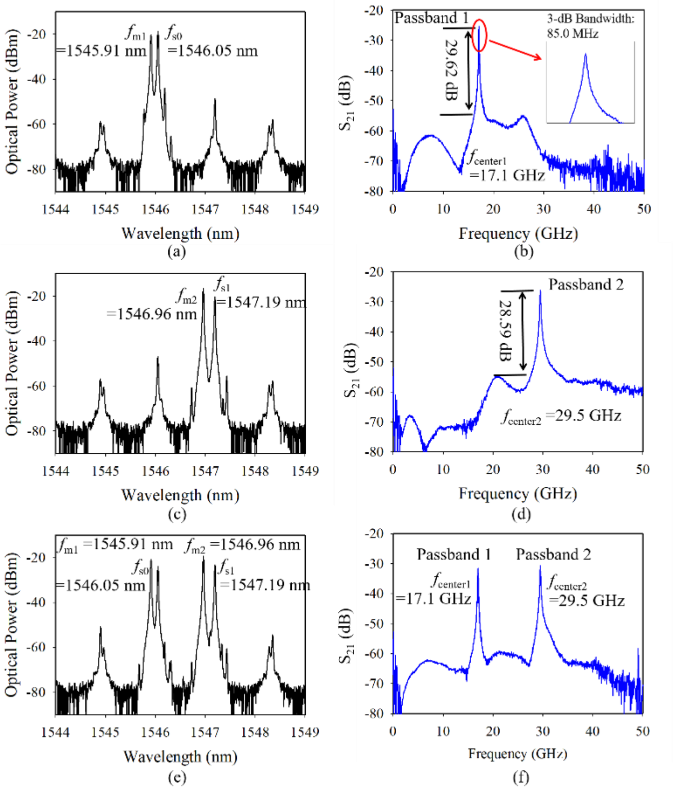

Fig. 3 Spectrum result of the proposed dual-passband MPF. (a), (c), and (e) shows the optical spectrum of MPF with f_{m1}, f_{m2} and both injection, respectively, whereas (b), (d) and (f) shows the frequency response result of (a),(c), and (e), respectively.

B. *The tunability analysis of the passbands of the proposed dual-passband MPF*

To demonstrate the tunability of the passbands of the proposed dual-passband MPF, firstly, the center frequency of passband2 is set constant at the frequency of 29.7 GHz and tuned the center frequency of Passband1. The deciding parameter for the center frequency of the passband is the wavelength of the injected beam. Hence, by changing the injected beam's wavelength, the respective passband's center frequency can be changed. Figure. 4(a) shows the tuning of the center frequency of Passband1 with Passband2 kept constant at 29.7 GHz. By changing the wavelength of the ML1, the center frequency of Passband1 is increased from 7.0 GHz to 42.0 GHz with a step of 5.0 GHz.

Similarly, the tuning of the Passband2 is obtained by changing the wavelength of ML2, keeping the center frequency of Passband1 constant at a center frequency of 37.0 GHz, as shown in Fig. 4(b). The center frequency of the Passband2 is tuned from 10.0 GHz to 45.0 GHz with a step of 5.0 GHz. Figure 4 illustrates that the center frequency of passbands can be changed independently to a wide range of about 35 GHz by simply varying the wavelength of injected beams. In the experiment, the gain spectrum of the SMFP-LD is constant as the control current and temperature are unchanged. Hence, the frequency of the injected beam decides the tunability of the proposed MPF. As the frequency detuning between the injected beam and the modes of the SMFP-LD increases, the center frequency of the passband in the proposed MPF increases. Hence, the passband of the proposed MPF has an extensive tuning range just by tuning the wavelength of the injected beam. Also, we observed that the tuning of one passband does not significantly affect the other passband filter response in terms of frequency stability and magnitude response. Independent tuning is possible because the tuning function is obtained by changing the wavelength of the injected beam. The different colored spectrum illustrates the tuning of the center frequency of one band, keeping another constant.

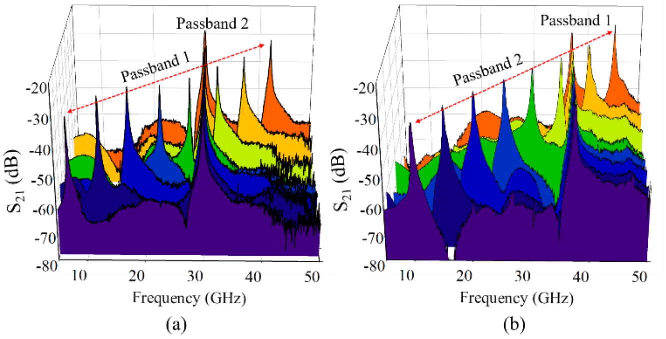

Fig. 4. Tuning of the center frequency of (a) Passband1 (b) Passband2

C. *Switching of the passbands of the dual-passband MPF*

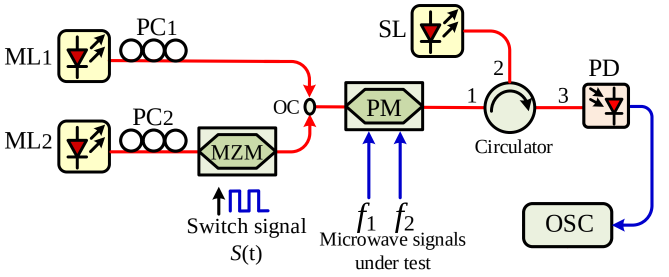

Fig. 5 The experiment setup for the switching of the passbands.

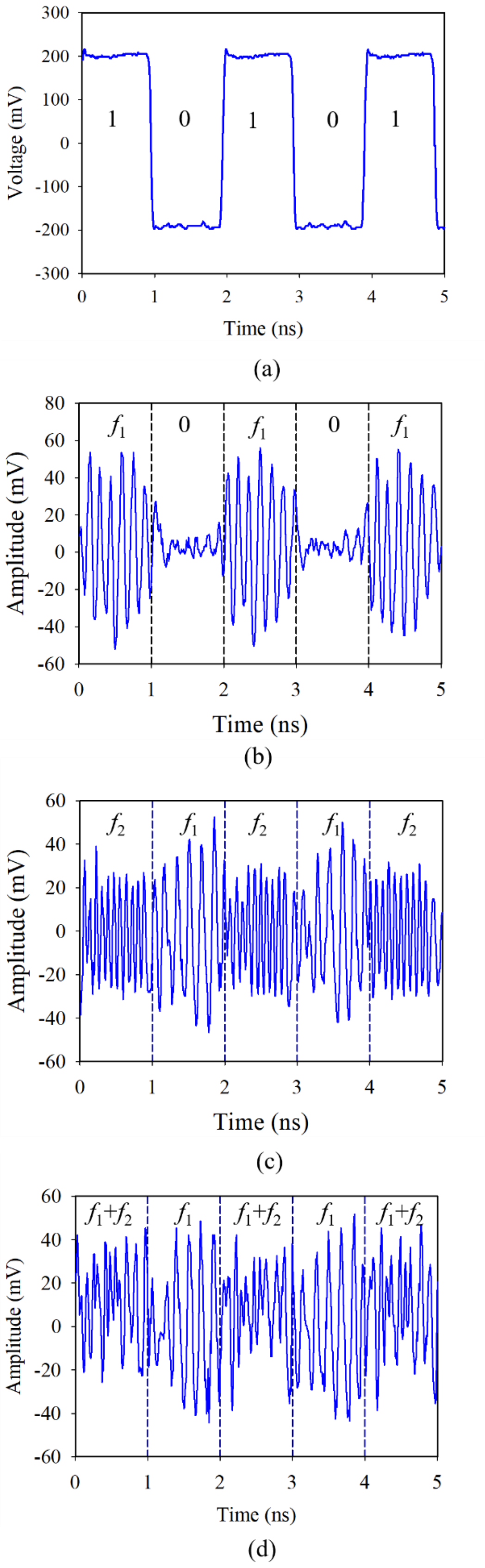

Fig. 6 The output result of the microwave signal under test processed by the switching of the passbands (a) switching signal of 1 Gbps (b) passband to no passband, (b) passband1 to passband2 and (d) two passband to one passband.

A proof-of-concept of switching on passbands of the proposed dual-passband MPF is illustrated in this section. Figure 5 shows the experimental setup for the switching of passbands of the proposed MPF. In Fig. 5, two microwave signals under test, f_1 and f_2, generated by a microwave signal generator, is sent to the phase modulator of the proposed MPF scheme., A real-time oscilloscope is used to measure the microwave signals under test at the output of the proposed MPF scheme. The ML2 is modulated by a switch signal S(t) through the modulator MZM to control the power of f_{m2}. The output of the passband switching is shown in Fig.6, where the switching signal of 1 Gbps is used.

At first, we demonstrate the switching of one passband to no passband of the MPF. For this purpose, we set the frequency of the microwave frequency under test, f_1 and f_2, as 6.2 GHz and 12.0 GHz. For a single passband MPF and switch the passband of MPF from one passband to no passband, the ML1 is set as OFF. Another external beam, ML2, is tuned in such a way that the frequency detuning of f_{m2} and f_{s1} equal to the center frequency of the passband, which is 6.2 GHz. With the applied control switching signal as shown in Fig. 6(a), the ML2 is amplitude modulated, as a result, when the control signal is “1”, the f_1 signal is passed to the output, and when it is “0”, the signal is blocked. Hence, at the output, the Passband2 is switched from Passband2 to no passband when the switching signal switch from “1” to zero and vice-versa, as shown in Fig. 6(b). Next, when ML1 and ML2 are present, and ML2 is modulated with the switching signal shown in Fig. 6(a), we observe the switching of Passband1 to Passband2 and vice versa. In this case, the wavelength of ML2 and ML1 is chosen so that the frequency detunings of ML1 and the dominant mode, ML2 and the first side mode, are 6.2 GHz and 12.0 GHz, respectively. Also, the power of ML2 is managed in such a way that SMFP-LD is in the strongly-injection locked state. Hence, the dominant mode of the SMFP-LD is suppressed. For strong injection locking of SMFP-LD, we set the power of f_{m1} and f_{m2} as 9.5 dBm and 13.5 dBm, respectively. Hence, when the switching signal is “1”, only Passband 2 is observed, and when the switching signal is “0”, only Passband1 is observed, as shown in Fig. 6(c). Next, the proposed MPF is demonstrated for two passband filters and switching from two passbands to one passband by weak injection-locking of SMFP-LD. To change from strong injection to weak injection, we decrease the power of f_{m2} from 13.5 dBm to 10.0 dBm and keep all other injection parameters constant. On weak injection-locking, the dominant mode of SMFP-LD is not suppressed. Hence, the output of the MPF is with two passbands and only Passband1 when the switch signal is “1” and “0”, respectively, and vice-versa, as shown in Fig. 6(d).

IV. CONCLUSION

In this paper, we propose and experimentally demonstrate a high-speed switchable dual-passband MPF subjected to dual-beam injection in an SMFP-LD. Two external beams are phase modulated to generate the +1st sideband and are simultaneously injected into two modes of the SMFP-LD with positive frequency detunings. Benefiting from the wavelength selective amplification effect of the SMFP-LD, the +1st sidebands of the modulated external beams are amplified when they lie in the gain bandwidth of the mode of the SMFP-LD. As a result, the generation of two passbands MPF with a center frequency equal to the frequency detuning of the injected beam and the corresponding mode of the SMFP-LD is observed. Further, we demonstrate the switching of passbands of the MPF, adding the switching unit with the MZM modulator and the switching signal. By properly setting the optical injection parameters of two external beams, the proposed MPF shows switching of its passbands from a single passband to no passband; one passband to another passband; and two passbands to one passband and vice versa. In the experiment, the center frequency of the passband MPF is tuned to the maximum frequency of 45.0 GHz, providing the tuning range of the passband as 35 GHz. The measured passband out-of-band rejection ratio and 3 dB bandwidth are about 29.62 dB and 85 MHz, respectively. The switching of the passband is performed at a speed of 1 Gbps. The switching speed depends on the relaxation oscillation of the semiconductor laser. For FP-LD, the maximum resonance frequency and switching time of 100 Gbps and 10 ps have been reported [24, 25]. Also, the switching time of less than 50 ps in SMFP-LD has been reported in our previous research [26]. Hence, we believe that the switching speed of passbands can be increased to further than 1 Gbps. The analysis of the maximum switching speed and the signal quality of the proposed passband filter will be carried out in our subsequent research work. Based on the demonstration, the demonstrated high-speed switchable dual-passbands MPF has an enormous potential for frequency hopping RADAR, complex signal processing in multifunctional radar, secure communication system, and radio-over-fiber system.

REFERENCES

[1] Zmuda H, Toughlian E N. “Photonic aspects of modern radar”. Artech House, Inc., 1994.

[2] Yao J. “Microwave photonics”. Journal of Lightwave Technology, 2009, 27(3): 314-335.

[3] Minasian R A. “Photonic signal processing of microwave signals”. IEEE Transactions on Microwave Theory and Techniques, 2006, 54(2): 832-846.

[4] Capmany J, Ortega B, Pastor D. “A tutorial on microwave photonic filters”. Journal of Lightwave Technology, 2006, 24(1): 201-229.

[5] Capmany J, Mora J, Gasulla I, et al. “Microwave photonic signal processing”. Journal of Lightwave Technology, 2013, 31(4): 571-586.

[6] J. Capmany and D. Novak, “Microwave photonics combines two worlds,” Nat. Photonics 1(6), 319–330 (2007).

[7] V. R. Supradeepa et al., “Comb-based radiofrequency photonic filters with rapid tunability and high selectivity,” Nature Photon., vol. 6, no. 3, pp. 186–194, 2012.

[8] Y. M. Zhang and S. L. Pan, “Complex coefficient microwave photonic filter using a polarization-modulator-based phase shifter,” *IEEE Photon. Technol. Lett.*, vol. 25, no. 2, pp. 187–189, Jan. 2013.

[9] L. Zhou, X. Zhang, E. Xu, Y. Yu, X. Li, and D. Huang, “A novel tunable cascaded IIR microwave photonic filter,” Opt. Commun., vol. 283, no. 14, pp. 2794–2797, 2010.

[10] Y. Jin et al., “Gigahertz single source IIR microwave photonic filter based on coherence managed multi-longitudinalmode fiber laser,” Opt. Exp., vol. 23, no. 4, pp. 4277–4288, 2015.

[11] H. Chen, Z. Xu, H. Fu, S. Zhang, C. Wu, H. Wu, H. Xu, and Z. Cai, “Switchable and tunable microwave frequency multiplication based on a dual-passband microwave photonic filter,” Opt. Express **23**(8), 9835–9843 (2015).

[12] H. Wang, J. Y. Zheng, W. Li, L. X. Wang, M. Li, L. Xie, and N. H. Zhu, “Widely tunable single-bandpass microwave photonic filter based on polarization processing of a nonsliced broadband optical source,” Opt. Lett. **38**(22), 4857–4860 (2013).

[13] E. Xu, S. Pan, Z. Zhang, and P. Li, “Performance-improved microwave photonic single-passband filter using birefringence of phase-shifted fiber Bragg grating,” Opt. Commun. **428**(1), 41–46 (2018).

[14] N. Shi, T. Hao, W. Li, N. Zhu, and M. Li, “A reconfigurable microwave photonic filter with flexible tunability using a multi-wavelength laser and a multi-channel phase-shifted fiber Bragg grating,” Opt. Commun. **407**(15), 27–32 (2018).

[15] S. Pan and J. Yao, “Wideband and frequency-tunable microwave generation using an optoelectronic oscillator incorporating a Fabry-Perot laser diode with external optical injection,” Opt. Lett. **35**(11), 1911–1913 (2010).

[16] Y. Yu, J. Dong, E. Xu, X. Li, L. Zhou, F. Wang, and X. Zhang, “Single passband microwave photonic filter with continuous wideband tunability based on electro-optic phase modulator and Fabry-Pérot semiconductor optical amplifier,” J. Lightwave Technol. 29(23), 3542–3550 (2011).

[17] J. Xiong et al., “A novel approach to realizing a widely tunable single passband microwave photonic filter based on optical injection,” IEEE J. Sel. Topics Quantum Electron., vol. 21, no. 6, pp. 171–176, Nov./Dec. 2015.

[18] Y. Deng, M. Li, J. Tang, S. Sun, N. Huang, and N. Zhu, “Widely tunable single-passband microwave photonic filter based on DFB-SOA-assisted optical carrier recovery,” IEEE Photon. J., vol. 7, no. 5, pp. 1–8, Oct. 2015.

[19] W. X. Wang, et al. “Tunable multiple-passband microwave photonic filter based on external optical injected Fabry-Pérot laser”. Optics Express, vol. 17, no. 9, 2019.

[20] Y. D. Jeong, Y. H. Won, S. O. ChoI, and J. H. Yoon, “Tunable single-mode Fabry-Perot laser diode using a built-in external cavity and its modulation characteristics,” Opt. Lett., vol. 31, no. 17, pp. 2586–2588, 2006.

[21] H. Chen, B. Nakarmi, M. Rakib Uddin, and S. L. Pan, “Optical Behavior Analysis of Negative Wavelength Detuning in SMFP-LD and Its Effect on Multi-RF Generation,” IEEE Photonics Journal, vol. 11, no. 1, 5500509, Feb. 2019.

[22] B. Nakarmi, S. L. Pan, and Y. H. Won, “Simultaneous Generation of Multiband Signals Using External Cavity-Based Fabry-Perot Laser Diode,” IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 1, pp. 606-617, Jan. 2018.

[23] L. Y. Chan, et al. “Demonstration of an all-optical switch by use of a multiwavelength mutual injection-locked laser diode”, Opt. Lett., vol. 28, pp. 837-839, May 2003.

[24] E. K. Lau, H. K. Sung, and M. C. Wu, “Frequency response enhancement of optical injection-locked lasers,” IEEE J. Quantum Electron. 44(1), 90–99 (2008).

[25] D. M. Gvozdić, M. M. Krstić, and J. V. Crnjanski, “Switching time in optically bistable injection-locked semiconductor lasers,” Opt. Lett. 36(21), 2011.

[26] B. Nakarmi, X. Zhang, Y. H. Won, “All-optical 4x10 Gbps NAND gate using single mode Fabry-Perot laser diode,” Opt. Exp., vol. 23, no.21, pp. 26952-26961, 2015.

[27]

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