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A multi-passband microwave photonic filter for sensing applications

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Abstract. In this paper, a multi-passband microwave photonic filter (MPF) for sensing applications has been proposed and experimentally demonstrated. The principle is based on a microwave photonic finite impulse response (FIR) filter. Multi passband can be achieved simply by cascading two Mach-Zehnder interferometers (MZIs) with different arm length difference. The variation of the length difference of MZI will change the free spectral range (FSR) of the optical spectrum, and resulting in the frequency variation of the passbands. Thus, by changing the arm length of the MZI using variable optical delay line (VODL), a high length measuring sensitivity of -2.796 GHz/mm has been achieved. Since different passbands have different measuring sensitivity, the MPF reveals the advantages of highly sensitive, and has broad application prospects in the field of optical sensing, especially multi-parameter sensing.

Keywords: microwave photonic filter, multi-passband, Mach-Zehnder interferometer, fiber sensing.

1. Introduction

Fiber-optic sensor with high measuring sensitivity is very critical in the field of physical and chemical parameters measurement. Compared with the traditional electrical or mechanical sensing techniques, fiber optic devices reveal the advantages including highly sensitive, compact structure, light weight and immunity to electromagnetic interference [1]. Today, the most common fiber-optic sensors are FBG sensors [2], interferometer sensors [3]. Although high sensitivity has been obtained, it is difficult for multi-parameter sensing and the resolution is limited since the interrogation is processed in optical domain.

Nowadays, with the development of microwave photonics, various microwave photonics based devices have been extensively investigated and explored [4], and more and more microwave photonic devices have been used for sensing applications, for example microwave photonic filter (MPF) sensors [5]. Meanwhile, the interrogation of this MPF based sensors is in frequency domain with higher resolution, which make it valuable in practical applications. Among MPFs, multi-passband MPF has been widely investigated since it can generate more than one passband simultaneously [6-7].



In this paper, we propose and experimentally demonstrate a tunable multi-passband MPF. The filter uses two cascaded MZI to splice the spectrum of the BBS to obtain optical taps with different wavelength spacing. By modulating the interfered light using a phase modulator and delayed with a dispersion device, a MPF with multi-passband is obtained. In the experiment, a SMF is taken as the delay device to study the filtering characteristics based on the structure. The tuning performance of each passband of the system is studied by adjusting the arm length difference of each MZI using the VODL in the system, which demonstrate the system shows a potential application in the area of multi-parameter sensing.

2. Principle of operation

Figure 1 is the schematic diagram of the multi-passband MPF based on cascaded MZIs. The optical signal from a broadband source (BBS) is sent into two cascaded MZI, which are composed of two identical optical couplers. To adjust the length difference between two arms of each MZI, two VODLs are inserted into one arm of each MZI. Thus, each the MZI consists of two OCs and a VODL. After filtering the spectrum by the cascaded MZIs, the signal is amplified by another EDFA and sent to a phase modulator (PM) for electro-optic modulation, and the RF input of the PM is provided by a network analyzer (VNA). After the optical signal is modulated by the RF signal generated by the VNA, it is dispersed by a SMF and converted into an electrical signal by the photodetector (PD). Finally, the frequency response is measured by the VNA.

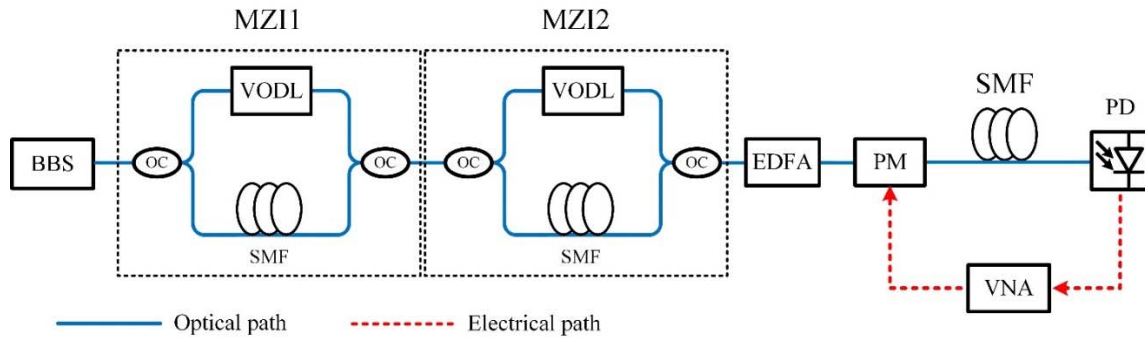


Fig.1 Schematic diagram of multi-passband microwave photonic filter

It has been demonstrated that the combination of a modulated two-beam interference spectrum, a dispersion device and the PD is equivalent to a finite impulse response (FIR) MPF with single passband [8]. Its central frequency equals to $f = 1/(D\Delta\lambda L)$, where D represents the group velocity dispersion parameter of the SMF, L is the SMF length. $\Delta\lambda$ is the FSR of the interference spectrum, which can be tuned by changing the length difference of the MZI. The FSR of the spectrum can be given by: $\Delta\lambda = \lambda^2 / (n_{\text{eff}}\Delta L)$, where λ is the central wavelength of the light source in vacuum, n_{eff} and ΔL are the effective fiber refractive index and the length difference between the two arms of the MZI, respectively. Thus, the central frequency of the passband of the MPF can be expressed as:

$$f = (n_{\text{eff}}\Delta L) / (D\lambda^2) \quad (1)$$

When two MZIs is cascaded, the light source will be divided into four different paths with different optical length. Then the four light beams will interfere at the output OC of MZI2. In this case, at most six different FSRs will generate and consequently, six passbands can be obtained in maximum. Moreover, as can be seen from Eq. (1), the frequency of the passband f is determined by the ΔL of the MZI and the L_{SMF} length of the SMF and is linearly proportional to the arm length difference ΔL .

By adjusting the delay of the VODL, the ΔL of MZI can be changed, as well as frequency of the generated passbands.

3. Experimental demonstration

The experimental verification of the MPF with multi-passband is carried out according to Fig. 1. The BBS is provided by the spontaneous emission spectrum of an EDFA with the output power of 16 dBm. Each MZI consists of two identical 3 dB OCs. Two VODLs are inserted into the MZI to control the arm length difference. After passing by the cascaded MZIs, the light is amplified by another EDFA. Then the signal is sent to a PM (Photline, MPZ-LN-40) for electro-optic modulation. The PM has a half-wave voltage of 7V. To verify the effectiveness of the scheme proposed in Fig. 1. A section of SMFs is used as the dispersion device. Finally, the optical signal enters the PD (Finisar, HPDV2120R) to complete photoelectric conversion. The lengths of the SMF is 20 km with the dispersion coefficients of 17 ps/(nm·km). Finally, the spectral response of the filter is obtained by VNA (Keysight, N5244A).

Fig. 2 shows the interference spectrum after the first MZI. It can be seen that the spacing of the adjacent wavelength is 1.62 nm, indicating the initial length difference of the MZI1 is 1.02 mm.

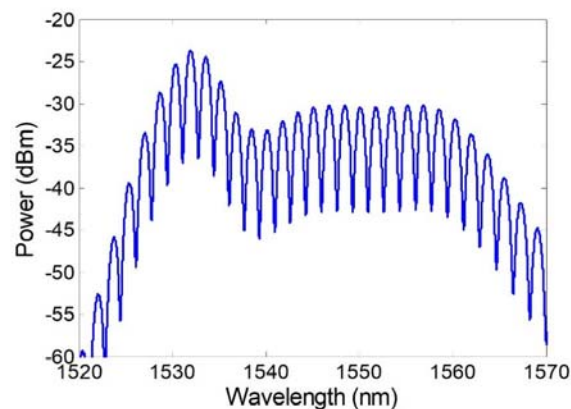


Fig. 2 Interference spectrum observed after the first MZI

Then the frequency response of the MPF is measured using the VNA, as shown in Fig. 3. Three frequency passbands with the central frequencies of 8.56 GHz, 16.13 GHz and 24.65 GHz can be observed within the frequency range from 0-40 GHz. According to Eq. (1), the experimental result agrees well with the theoretical analysis. The SMSR of all the three passbands are over 20 dB.

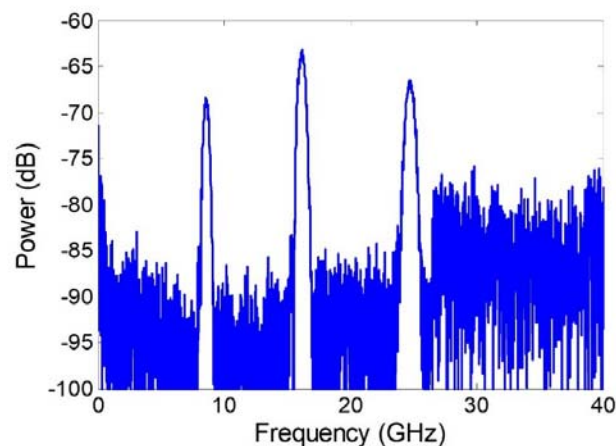


Fig. 3 Frequency response of the multi-passband MPF

Then the tuning ability of the system is investigated. It can be seen from Eq. (1) that the central frequency of the passband is determined by the arm length difference ΔL of each MZI. Thus, the central frequency of the passbands can be changed simply by adjusting the arm length difference in terms of the two VODLs. First, we investigate the frequency response in respect to the length change caused by VODL1. By tuning the delay of the VODL1 and keep the delay of the VODL2 unchanged, the frequency tunability of the passbands changes accordingly, which is shown in Fig. 4(a).

It can be seen from that the central frequency of passband 1 and passband 3 decreases from 10.52 GHz to 6.39 GHz and 25.74 GHz to 21.74 GHz as the arm length increases, while the central frequency of passband 2 keeps almost stable. The result demonstrates the tuning ability of the system. Moreover, similar result has been achieved by tuning the delay of the VODL2 and keeping the delay of the VODL2 unchanged, as shown in Fig. 4(c). As illustrated in the figure, the central frequency of passband 1 increases from 9.27 GHz to 17.58 GHz as the length change increase from 0 mm to 3.5 mm, and the central frequency of passband 2 decreases from 15.48 GHz to 7.01 GHz. Meanwhile, the location of the passband 3 remains stable during the tuning process.

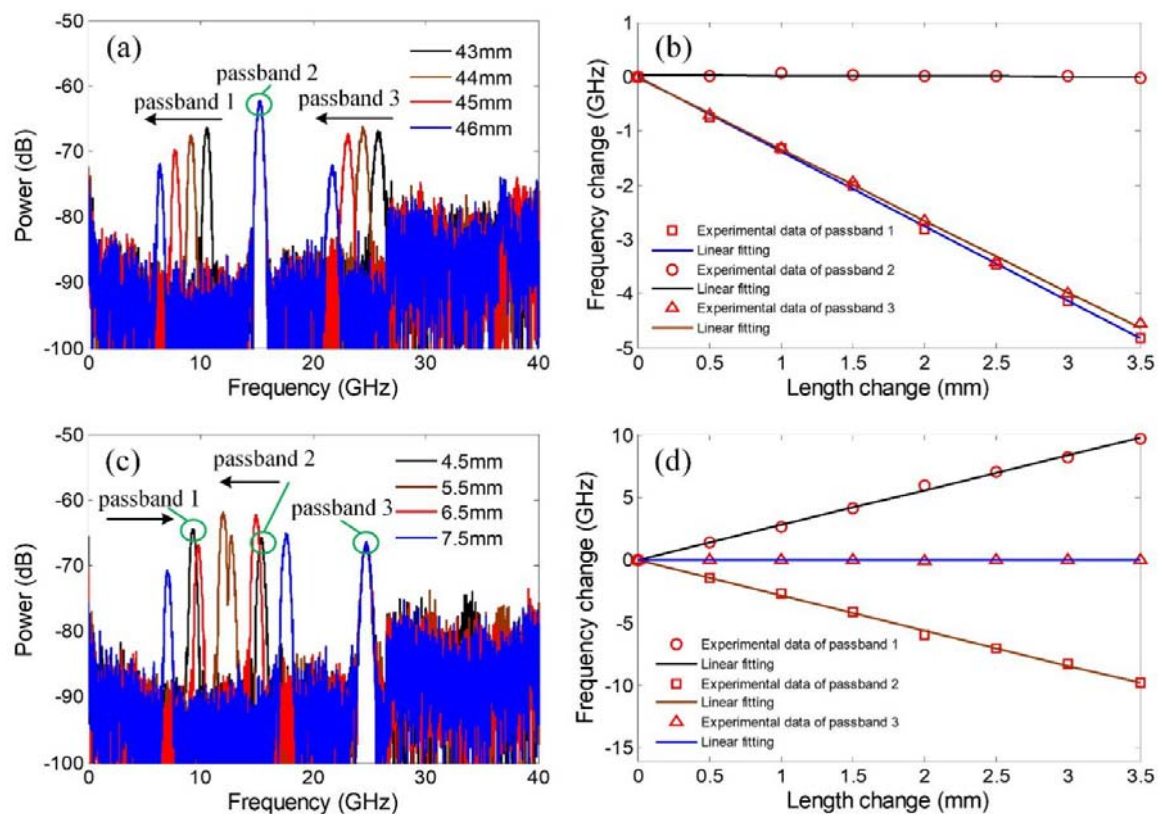


Fig. 4 (a) Superposition of MPF frequency response with different length difference of MZI1; (b) Measured frequency variation of different passbands with the arm length change caused by the VODL1; (c) Superposition of MPF frequency response with different length difference of MZI2; (d) Measured frequency variation of different passbands with the arm length change caused by the VODL2

The relationship between measured frequency change variation and the length change is shown in Fig. 4(b). It can be found that the frequency of the passband 1 and passband 3 decreases almost linearly with a responsivity of -1.3786 GHz/mm and -1.3181 GHz/mm with very high correlative coefficient of 0.9996 and 0.9994. As illustrated in the figure, the central frequency of passband 1 increases from 9.27

GHz to 17.58 GHz as the length change increase from 0 mm to 3.5 mm with a sensitivity of 2.7782 GHz/mm, and the central frequency of passband 2 decreases from 15.48 GHz to 7.01 GHz with a sensitivity of -2.7963 GHz/mm. Meanwhile, the location of the passband 3 remains stable during the tuning process.

In order to further analyze the specific relationship between the central frequency of each passband and length change, the measured frequency change in response to the length change caused by each VODL is recorded. It can be found that in Fig. 4(b), by changing the length of VODL1, the frequency of the passband 1 and passband 3 decreases almost linearly with a responsivity of -1.3786 GHz/mm and -1.3181 GHz/mm with very high correlative coefficient of 0.9996 and 0.9994. Moreover, by adjust the length of VODL2, the central frequency of passband 1 increases with a sensitivity of 2.7782 GHz/mm, and the central frequency of passband 2 decreases with a sensitivity of -2.7963 GHz/mm, as depicted in Fig. 4(d). The results indicate that the central frequencies of the multi-passband can be tuned simply by changed the length difference of each MZI, which shows great potential in the application of optical multi-parameter sensing. As the environmental parameter for example temperature, axial strain changes, the length of the fiber changes correspondingly, as well as the frequency of the generated passbands.

4. Conclusion

In this paper, we present a tunable MPF with multi-passband based on a spliced light source. The multi-passband MPF is realized by cascading two MZIs with different arm length difference. The results demonstrate that the frequency of the generated passband can be changed almost linearly with the variation of the arm length of the MZI. A very high measuring sensitivity of -2.796 GHz/mm has been achieved. The tuning performance indicates that the MPF can be used in the sensing, especially in the situation that more than two or more parameters must be detected simultaneously. The multi-passband MPF proposed in this paper is easy to implement, and has good tunability and stability. Thus, it has a wide range of applications in modern wireless and satellite communication, multi-carrier optoelectronic oscillator and optical sensing.

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