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A microwave photonic filter based on multi-wavelength fiber laser and infinite impulse response*

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A microwave photonic filter (MPF) based on multi-wavelength fiber laser and infinite impulse response (IIR) is proposed. The filter uses a multi-wavelength fiber laser as the light source, two sections of polarization maintaining fiber (PMF) and three polarization controllers (PCs) as the laser frequency selection device. By adjusting the PC to change the effective length of the PMF, the laser can obtain three wavelength spacings, which are 0.44 nm, 0.78 nm and 1.08 nm, respectively. And the corresponding free spectral ranges (*FSRs*) are 8.46 GHz, 4.66 GHz and 3.44 GHz, respectively. Thus changing the wavelength spacing of the laser can make the *FSR* variable. An IIR filter is introduced based on a finite impulse response (FIR) filter. Then the 3-dB bandwidth of the MPF is reduced, and the main side-lobe suppression ratio (*MSSR*) is increased. By adjusting the gain of the radio frequency (RF) signal amplifier, the frequency response of the filter can be enhanced.

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Microwave photonic filters (MPFs) are extensively applied in communication and radar systems[1-3]. Some important characteristics of the filter can be realized by using the appropriate light source. The MPF with the broadband light source cut by Bragg grating array can achieve the reconfigurability of the MPF[4,5]. If the broadband source is cut by a Mach-Zehnder interferometer (MZI), the center frequency of the MPF can be tuned[6]. A tunable laser can be used to achieve tunability[7,8]. Laser array can achieve rapidly and independently tunable and reconfigurable characteristics[9]. Compared with broadband light source and laser array, the multi-wavelength fiber laser has the advantages of low cost, simple structure, and flexible operation. Therefore, the MPFs based on multi-wavelength laser become research hotspots in this field. Jingjing Wang[10] achieved a multi-wavelength laser based on recirculation frequency shifting loop, and then got an MPF with a large tuning range. Wenhui Sun[11] changed the number of wavelengths of the multi-wavelength laser by tuning the pump power. Then reconfigurability of the MPF was realized. Kok Kuen Loh[12] introduced a multi-wavelength Brillouin laser into the MPF. The MPF's 3-dB bandwidth resolution reached 24 MHz by controlling the number of the wavelengths of the multi-wavelength laser. According to the number of the light taps, the MPF can be divided into the finite impulse response (FIR) filter and the infinite impulse response (IIR) filter. If a multi-wavelength fiber laser is made as the light source, MPF is generally an FIR filter. By forming a loop circuit in the structure, an IIR filter can be obtained[13-15]. In this way, Zhou Lina[16,17] and Zhang Ailing[18] achieved high Q value, and the frequency response of the MPF has been greatly improved.

In this letter, a multi-wavelength fiber laser with variable wavelength spacing is used as light source of the MPF. By adjusting the polarization controller (PC) to get different polarization maintaining fiber (PMF) effective lengths, the laser can output three wavelength spacings, so that the filter can get three free spectral ranges (*FSRs*). With the radio frequency (RF) signal, which is converted by photodetector (PD), refilling into the dual-driven Mach-Zehnder modulator (DDMZM), an electrical feedback IIR filter is introduced to the MPF. Thus 3-dB bandwidth and *MSSR* of the MPF are improved effectively. By adjusting the gain of the RF signal amplifier, the frequency response of the filter can be enhanced.

The system configuration of the proposed MPF is shown in Fig.1. It includes a multi-wavelength laser and an electrical feedback IIR filter.

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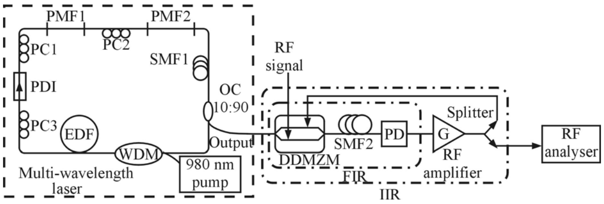

Fig.1 The system configuration of the proposed microwave photonic filter

The multi-wavelength lasing is produced via a ring cavity. The cavity is composed of a 980 nm pump source, a wavelength division multiplexer (WDM), erbium doped fiber (EDF), a polarization dependent isolator (PDI), single mode fiber (SMF), three PCs, two sections of PMF and a 10:90 optical coupler (OC). The mode competition in EDF can be suppressed effectively based on nonlinear polarization rotation to make sure multi-wavelength output. PDI can also ensure the light transmission along the same direction. Then 10% of the lasing is output from the 10:90 OC.

We introduce two sections of PMF into the multi-wavelength laser for adjusting the wavelength spacing. L_1 and L_2 are the lengths of PMF1 and PMF2, respectively. The relationship between wavelength spacing and PMF effective length is

$$\Delta\lambda = \frac{\lambda^2}{\Delta n \cdot L}, \tag{1}$$

where $\Delta\lambda$ is the wavelength spacing, λ is the center wavelength of output lasing, Δn is the birefringence of PMF, and L is the effective length of PMF. By changing the polarization angle of PC2, we could obtain four different effective lengths of PMF theoretically, which are L_1, L_2, $|L_1-L_2|$ and L_1+L_2. The corresponding wavelength spacing varies with the adjustment of PC2. We could obtain different numbers of wavelengths by adjusting the pump power. Since the gain-bandwidth of EDF is limited, the number of wavelengths of the multi-wavelength laser is finite.

The multi-tap lasing from the multi-wavelength laser is sent to the DDMZM. The output signal is delayed by SMF2 and then reaches PD. The DDMZM has two driven ports, one is connected to an RF signal generator, while the other port is connected to the output port of the PD to form a recirculation loop, thus the converted RF signal by the PD is fed back to the DDMZM. According to the signal flow graph theory, the transfer function of IIR filter is

$$H_1(z) = \frac{kL^*}{1-(1-k)Gz^{-1}}, \tag{2}$$

where L^* is the total loss including the insertion losses of the RF power divider, the modulator and the optical fibers, G is the gain of the RF amplifier, and k is the split ratio of the RF power splitter. The FIR transfer function is

$$H_2(z) = \sum_{n=1}^{N} P_n z^{-(n-1)}, \tag{3}$$

where N is the number of the taps of the light source, and P_n is the power of each tap, where n=1, 2, …N. The total transfer function of the cascaded IIR and FIR filters is

$$H(z) = H_1(z)\cdot H_2(z) = \frac{kL^* \cdot \sum_{n=1}^{N} P_n z^{-(n-1)}}{1-(1-k)Gz^{-1}}. \tag{4}$$

According to Eq.(4), the time delay difference between each two taps of the FIR filter is equal to that between each two taps of the IIR filter. With $z=\exp(\mathrm{j}2\pi Tf_{\mathrm{m}})$, Eq.(4) can be rewritten in frequency domain as

$$H(f_{\mathrm{m}}) = \frac{kL^* \cdot \sum_{n=1}^{N} P_n \exp\left[-\mathrm{j}2\pi(n-1)Tf_{\mathrm{m}}\right]}{1-(1-k)G\exp(-\mathrm{j}2\pi Tf_{\mathrm{m}})}, \tag{5}$$

where T is the time delay difference between each two taps and f_{m} is the RF frequency.

In our experiment, we have two sections of PMF with the lengths of 4 m and 10 m, respectively. The birefringence of the PMF is 5.1×10^{-4}. The length of EDF is 4 m. By adjusting PC2, we obtain the lasing with three different wavelength spacings, which are 0.44 nm, 0.78 nm and 1.08 nm. The wavelength spacings of 0.44 nm and 0.78 nm are shown in Fig.2 and Fig.3, respectively, and the number of wavelengths is 8. By adjusting the pump power, the lasing with different wavelength numbers is obtained. Fig.4 shows the 1.08 nm wavelength spacing with three wavelengths, and Fig.5 shows the 1.08 nm wavelength spacing with five wavelengths.

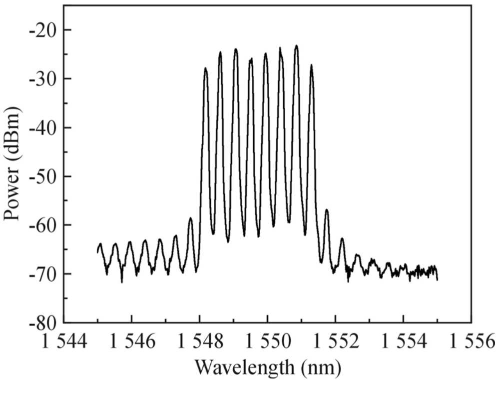

Fig.2 The multi-wavelength laser with 0.44 nm wavelength spacing

The IIR filter uses electrical feedback, so the main time delay is caused by the FIR filter. 15-km-long SMF2 is included in the FIR filter, which is used as a time delay component. The FSR of the filter is

$$FSR = \frac{1}{T} = \frac{1}{D\cdot\Delta\lambda\cdot l}, \tag{6}$$

where T is the time delay between each two taps, D and l

are dispersive coefficient and physical length of the SMF2, respectively, and $\Delta\lambda$ is the wavelength spacing. According to Eq.(6), when $\Delta\lambda$ is changed, T will be changed, so we could obtain different *FSRs*. The frequency responses of the MPF with different wavelength spacings are presented in Fig.6. The *FSRs* are 3.44 GHz, 4.66 GHz and 8.46 GHz, when the wavelength spacings are 1.08 nm, 0.78 nm and 0.44 nm, respectively.

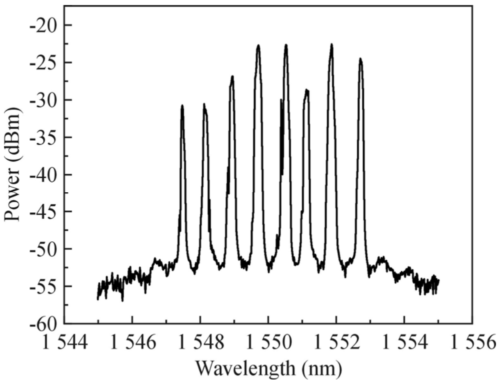

Fig.3 The multi-wavelength laser with 0.78 nm wavelength spacing

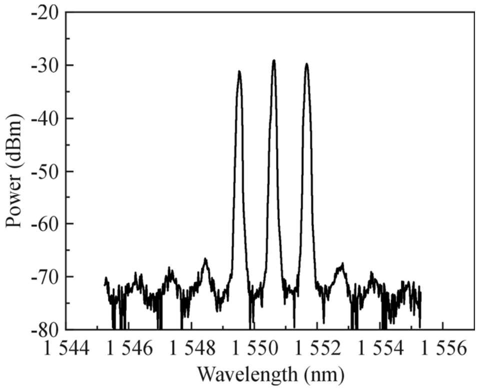

Fig.4 1.08 nm wavelength spacing with three wavelengths

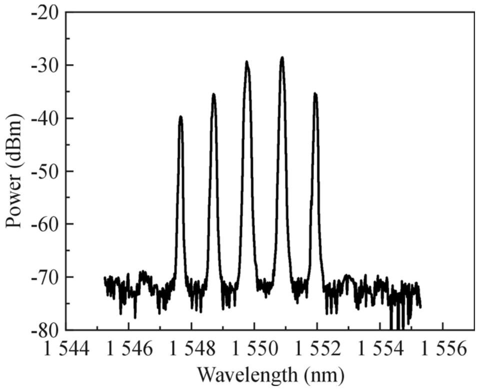

Fig.5 1.08 nm wavelength spacing with five wavelengths

When the lasing has six taps, the wavelength spacing is 0.78 nm, and the values of G, k and L^* are 1.75, 0.5 and 0.22, respectively. The frequency responses calculated based on Eq.(5) are shown in Fig.7. We could see that the IIR filter and the FIR filter have the same *FSR*, and they make up the response of the MPF together. Compared with the FIR filter only, the frequency response of the cascaded filter has a bit lower power, but its 3-dB bandwidth is decreased by 660 MHz and *MSSR* is increased by 9.98 dB.

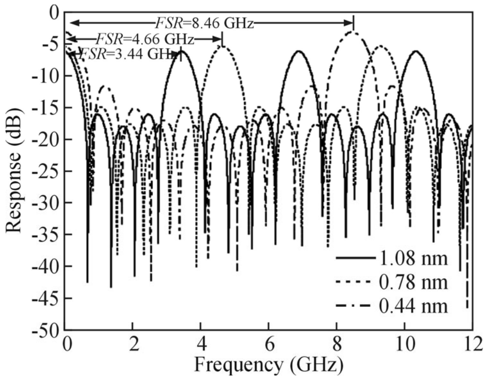

Fig.6 The frequency responses of the MPF with different wavelength spacings

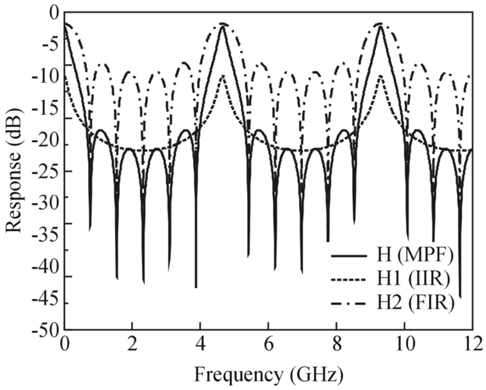

Fig.7 The frequency responses of the MPF, IIR and FIR

We could change the *FSR* by adjusting the wavelength spacing of the laser, and realize the reconfiguration by changing the number of wavelengths. When the RF amplifier gain G is changed, the frequency response is also changed. Fig.8 shows the frequency responses for dif-

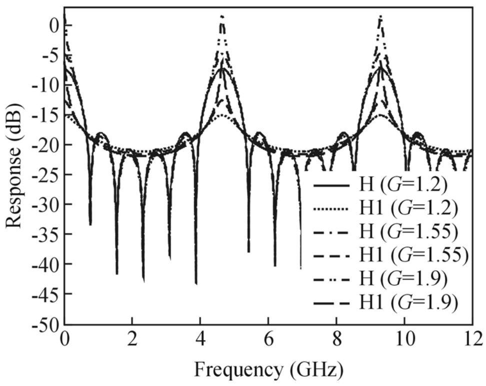

Fig.8 The frequency responses with different RF amplifier gains

ferent *G* values. When *G* equals 1.2, the 3-dB bandwidth is 730 MHz and *MSSR* is 11.20 dB. When *G* equals 1.55, the 3-dB bandwidth is 530 MHz and *MSSR* is 13.52 dB. When *G* equals 1.9, the 3-dB bandwidth is 190 MHz and *MSSR* is 20.39 dB. Thus the frequency response has different 3-dB bandwidths and *MSSRs* by changing the RF amplifier gain, and the peak power is also changed. Therefore, adjusting the RF amplifier gain makes it easier to realize reconfiguration.

We propose an MPF based on a multi-wavelength fiber laser and an IIR filter. We can get three different wavelength spacings by adjusting the PC between two sections of PMF. Then three different *FSRs* of the MPF are obtained. With the electrical feedback IIR filter, the response of the MPF has been improved effectively. We can easily change the passband characteristics by adjusting the gain of the RF signal amplifier.

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