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Reconfigurable and tunable multi-tap bandpass microwave photonic filter based on a hybrid-gain-assisted multi-wavelength fiber ring laser

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A reconfigurable and tunable multi-tap bandpass microwave photonic filter based on a hybrid-gain-assisted multi-wavelength fiber ring laser (HMFRL) is proposed and experimentally demonstrated. The HMFRL containing a hybrid gain medium and a high birefringence fiber loop mirror serves as the multiple taps generator for the microwave photonic filter. In order to realize a bandpass filter, the multiple taps are phase modulated, then the modulated signal is launched into a coil of dispersion compensating fiber to introduce different time delays for each tap. As a result, a bandpass response is obtained at the output of a high speeding photodetector. By adjusting the bias of the semiconductor optical amplifier from 344 to 450 mA, the number of multiple taps can be increased without optical signal-to-noise ratio degradation. Thus, a multi-tap bandpass microwave photonic filter with bandwidth reconfiguring from 449 to 274 MHz is achieved. In addition, by changing the length of polarization maintaining fiber in the high birefringence fiber loop mirror, the wavelength spacing of the multiple taps can be adjusted, making the bandpass microwave photonic filter's free spectral range tunable.

Keywords: microwave photonic filter, multi-wavelength fiber ring laser, microwave signal processing.

1. Introduction

Microwave photonic filter (MPF) is one of the most important microwave photonic processing subsystems, it has been intensively studied in the past few years [1–3]. Compared with a traditional microwave filter implemented in electrical domain, MPF has many unique characteristics, such as low loss, large bandwidth, seamless tunability, good reconfigurability and immunity to electromagnetic interference (EMI). In recent years, a number of MPFs have been implemented by using multi-wavelength optical source in cooperation with dispersive medium [4–6]. The frequency response of MPF can be controlled by altering the dispersion of the multiple taps, or changing the relative amplitude as well as the wavelength spacing of them. In general, single mode fiber (SMF), dispersion compensating fiber (DCF) or chirped fiber Bragg grating (CFBG) are used as a dispersive medium. As for a multi-wavelength optical source, an optical tunable laser diodes (TLDs) array is an original way to generate multiple taps, and the control of multiple taps can be easily realized in this way, but TLDs array leads to a high cost in practical application [7]. For other approaches, broadband source slicing [8–10], multi-wavelength fiber ring lasers [5, 11, 12] are also commonly utilized to serve as a multiple taps generator. In [8], multiple taps were obtained by slicing the broadband source using reflective and cascaded fiber Mach–Zehnder interferometers (MZIs). An MPF with tunable and selectable multiple passbands was realized, but the stability of MZI was hard to be ensured at room temperature, and high insertion loss might be incurred. In [11], the authors used a windowed Fabry–Pérot filter-based multi-wavelength tunable laser to generate multiple taps, and a tunable multi-tap bandpass MPF was achieved, where the center frequency of the MPF can be tuned by adjusting the Fabry–Pérot filter in a programmable manner. However, the tuning process was limited by the step of the Fabry–Pérot filter, making the tunability discontinuous. Except for these methods, four-wave mixing (FWM) is an effective way to increase the number of optical taps for MPFs, and the relative amplitude or the wavelength spacing of multiple taps can be easily controlled. A reconfigurable MPF based on FWM was realized by adjusting the gain of an optical amplifier and the state of polarization. The relative amplitude of the multiple taps can be adjusted, thus, the shape of MPF can be controlled [13]. Another approach to realizing a widely tunable MPF based on FWM was also proposed [14] by changing the wavelength spacing of multiple taps. Here, the free spectral range (FSR) of the MPF can be continuously tuned, but the shape of MPF is changed obviously while tuning the FSR.

In this paper, we propose and demonstrate a reconfigurable and tunable multi-tap bandpass MPF, which is based on a hybrid-gain-assisted multi-wavelength fiber ring laser (HMFRL). The HMFRL containing a hybrid gain medium and a high birefringence fiber loop mirror (Hi-Bi FLM) serves as a multiple taps generator for the MPF. A semiconductor optical amplifier (SOA) and an erbium-doped optical fiber amplifier (EDFA) are used to provide the hybrid gain, and the Hi-Bi FLM acts as the wavelength selection component. By adjusting the bias of SOA, the number of multiple taps can be increased without optical signal-to-noise ratio (OSNR) degradation, leading to the bandpass MPF's bandwidth reconfiguring. In addition, by changing the length of polarization maintaining fiber (PMF) in the Hi-Bi FLM, the wavelength spacing of the multiple taps can be adjusted, making the bandpass MPF's FSR tunable.

2. Experimental setup and principle

The schematic diagram of the proposed multi-tap bandpass MPF is shown in Fig. 1. The HMFRL contains a hybrid gain medium and a Hi-Bi FLM. An SOA and an EDFA (EDFA1) are used to provide a hybrid gain. The amplified spontaneous emission (ASE) generated from SOA and EDFA1 is amplified and propagates through the Hi-Bi FLM.

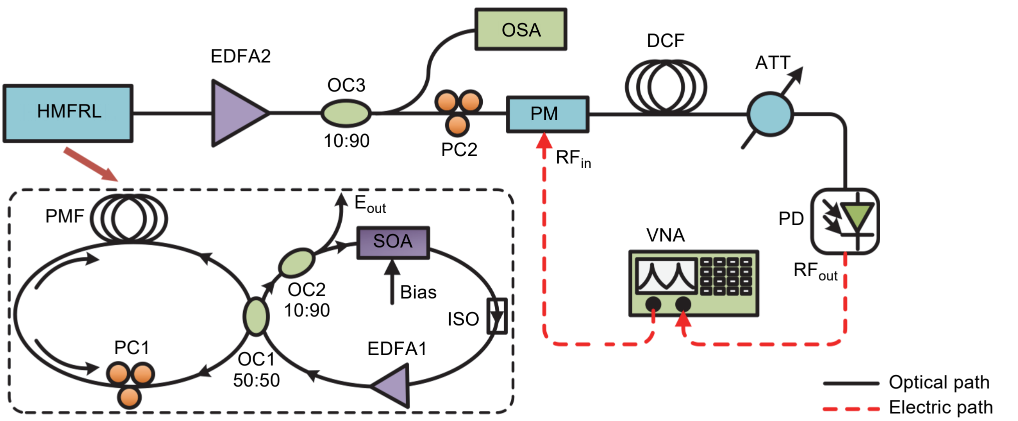

Fig. 1. The schematic diagram of the proposed MPF. PMF – polarization maintaining fiber, PC – polarization controller, OC – optical coupler, SOA – semiconductor optical amplifier, ISO – isolator, EDFA – erbium-doped optical fiber amplifier, OSA – optical spectrum analyzer, PM – phase modulator, DCF – dispersion compensating fiber, ATT – optical attenuator, PD – photodetector, VNA – vector network analyzer.

The Hi-Bi FLM is configured by a 50:50 optical coupler (OC, OC1), a polarization controller (PC, PC1) and a length of PMF, it serves as a comb filter for multi-wavelength selection. Multi-wavelength oscillations at each peak of the Hi-Bi FLM transmission spectrum will be strengthened, leading to multi-wavelength lasering. Since SOA serves as an inhomogeneous broadening gain medium at room temperature, it can effectively reduce model competition, and the stable multi-wavelength operation can be realized [15–17]. Then the multi-wavelength output is power-amplified by an EDFA2. The output of 10% from EDFA2 is injected into an optical spectrum analyzer (OSA) for optical spectrum monitoring, and 90% is used as multiple taps for the MPF. Then the multiple taps are phase-modulated by an input RF signal emitted from a vector network analyzer (VNA). The phase-modulated signal is then launched into a coil of DCF, which acts as a wideband dispersive medium. PC2 is used before the phase modulator (PM) to minimize the polarization-dependent loss. Finally, the microwave signals can be recovered by a high speeding photodetector (PD). An optical attenuator (ATT) is connected to keep the input power into the PD less than 0 dBm for the sake of security of the system. The corresponding frequency response of the proposed MPF can be obtained as S_{21} parameter in the VNA.

The frequency response $H(f_{\mathrm{RF}})$ of the multi-tap bandpass MPF using a conventional optical phase modulation can be indicated as

$$H(f_{\mathrm{RF}}) \propto R\cos\left(\frac{\pi D_m L \lambda_m^2 f_{\mathrm{RF}}^2}{c} + \frac{\pi}{2}\right) \sum_{m=1}^{M} P_m \exp\left[j2\pi f_{\mathrm{RF}}(m-1)\Delta\tau\right] \quad (1)$$

where R is the responsivity of PD, f_{RF} is the modulation frequency, D_m is the accumulated dispersion for the m-th optical carrier, L is the length of DCF, λ_m is the wavelength of the m-th optical carrier, c is the speed of light wave in vacuum, P_m is the power of the m-th optical carrier, M is the number of multiple taps, and $\Delta\tau$ is the time delay difference between the adjacent taps introduced by the dispersive medium. As indicated in Eq. (1), the MPF can be reconfigured by changing the number of multiple taps.

The FSR of the multi-tap bandpass MPF can be expressed as

$$\text{FSR} = \frac{1}{DL\Delta\lambda} \tag{2}$$

where D and L are the dispersion coefficient and the length of DCF, respectively, $\Delta\lambda$ is the wavelength spacing of the multiple taps. From Eq. (2), for a given length of dispersive medium, FSR of the bandpass MPF can be tuned by adjusting the wavelength spacing of multiple taps. Since the Hi-Bi FLM serves as a comb filter for multi-wavelength output selection in this scheme, the wavelength spacing of multiple taps is equal to that of the Hi-Bi FLM transmission spectrum, which can be expressed as

$$\Delta\lambda = \frac{\lambda^2}{\Delta n L_{\text{eff}}} \tag{3}$$

where Δn is the effective birefringence between two orthogonal polarization modes and L_{eff} is the effective length of PMF. As can be seen in Eq. (3), the wavelength spacing is inversely proportional to the length of PMF. Thus, the wavelength spacing of multiple taps can be varied by changing the length of PMF. And the FSR tunability of the proposed bandpass MPF is achieved.

3. Results and discussion

The key parameters of the devices used in the experiment are summarized as follows: the PM (Photline MPZ-LN-20) has a 3-dB bandwidth of 20 GHz. The DCF (DCF-G.652 C/250) has a length of 2.05 km and a chromatic dispersion of 332.07 ps/nm. The SOA (SOA1117) is biased on 180 mA and can provide small signal gain of about 17 dB, which can be driven at maximum current of 500 mA. The birefringence ratio of the PMF (PMP-1550-1-PM1550-FU-FA) is 0.0004. The resolution of OSA (Anritsu MS9740A) is 0.03 nm. The high speeding PD (u2t XPDV2120R) has a bandwidth of 40 GHz. The microwave signal emitted from the VNA (CETC, AV3629D) is sweeping from 45 MHz to 20 GHz.

Since the number of multiple taps can be varied by adjusting the bias of SOA, a multi-tap bandpass MPF with reconfigurable bandwidth is achieved. Figures 2**a** and 2**b** show the optical spectrum of multiple taps when the bias of SOA is set as 344 and 450 mA, respectively. The full span of the spectrum is 40 nm. Because the length of PMF is fixed at 6 m, both of the wavelength spacings in Figs. 2**a** and 2**b** are equal to 0.97 nm, which shows good agreement with the theoretical value (1.001 nm) calculated according to Eq. (3). As can be seen, when the bias of SOA is increased, the number of multiple taps increase apparently. The reason is that the SOA provides less gain spec-

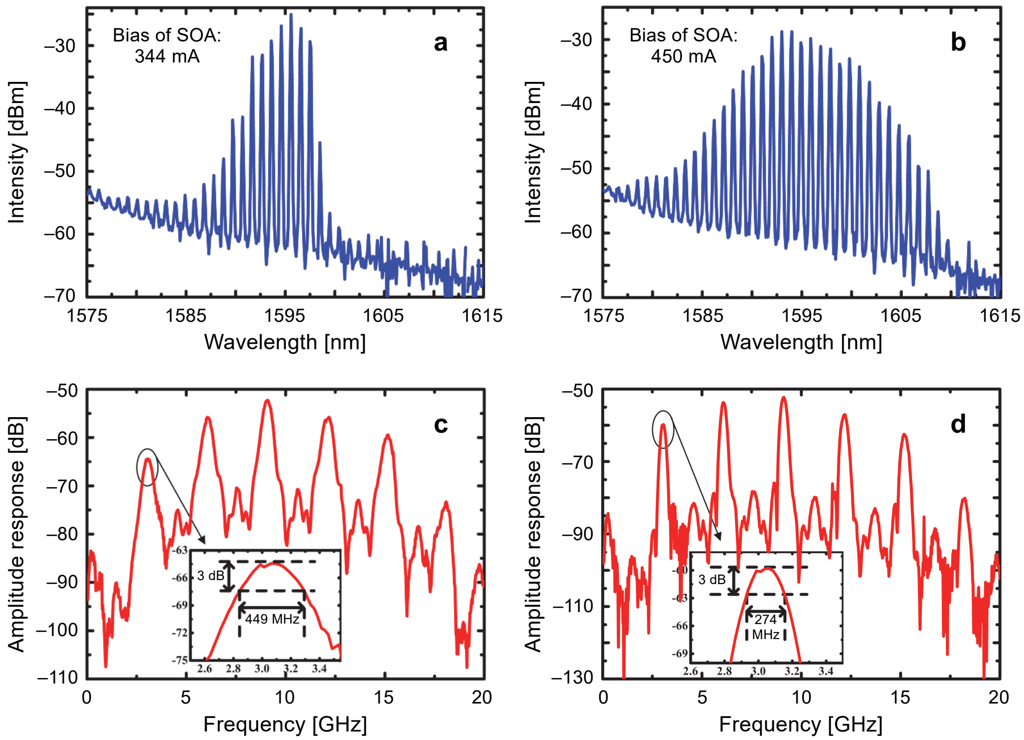

Fig. 2. Measured optical spectrums of multiple taps: the bias of SOA is set as 344 mA (**a**) and 450 mA (**b**). The corresponding frequency responses of the multi-tap bandpass MPF (**c**, **d**). Inset – the zoom-in view of the first passband.

trum with lower bias [18]. The measured corresponding frequency responses are shown in Figs. 2**c** and 2**d**, respectively. The frequency response of the MPF is periodic, and the value of FSR is equal to the center frequency of the first passband [14]. One can see that the 3-dB bandwidth of the passbands is narrowed from 449 to 274 MHz when the bias of SOA is adjusted from 344 to 450 mA. Note that amplitude fading of the experimental passbands is existing, it is caused by the dispersion slope of the DCF [5]. This phenomenon can be avoided by using single sideband (SSB) intensity modulation, but the value of the frequency response of the MPF would not be equal to zero at $f_{RF} = 0$ when adopting intensity modulation, which would sacrifice the baseband suppression at dc.

The 3-dB bandwidth of the passbands can be plotted as a function of the bias of SOA, as shown in Fig. 3. When the bias of SOA is set at 344, 353, 373, 393, 423, 443, and 450 mA, the corresponding 3-dB bandwidths are 449, 424, 399, 349, 324, 299, and 274 MHz, respectively. As the blue curve indicates, when the bias of SOA increases, the 3-dB bandwidth of the passbands decreases. That is to say, the 3-dB bandwidth shows inversely proportional linear dependence with the bias of SOA. Therefore, the narrower bandwidth or the higher Q-factor can be realized with the greater number of

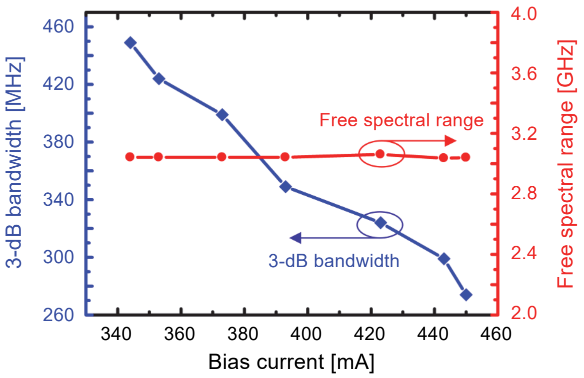

Fig. 3. The 3-dB bandwidth and FSR of the MPF with different bias of SOA.

taps. The red curve shows that although the bias of SOA increases, the FSR of the multi-tap bandpass MPF remains particularly constant, which is fixed around 3.042 GHz.

Next, the tunability of the proposed multi-tap bandpass MPF is investigated. The bias of SOA is fixed at 450 mA. The wavelength spacing of multiple taps can be varied by

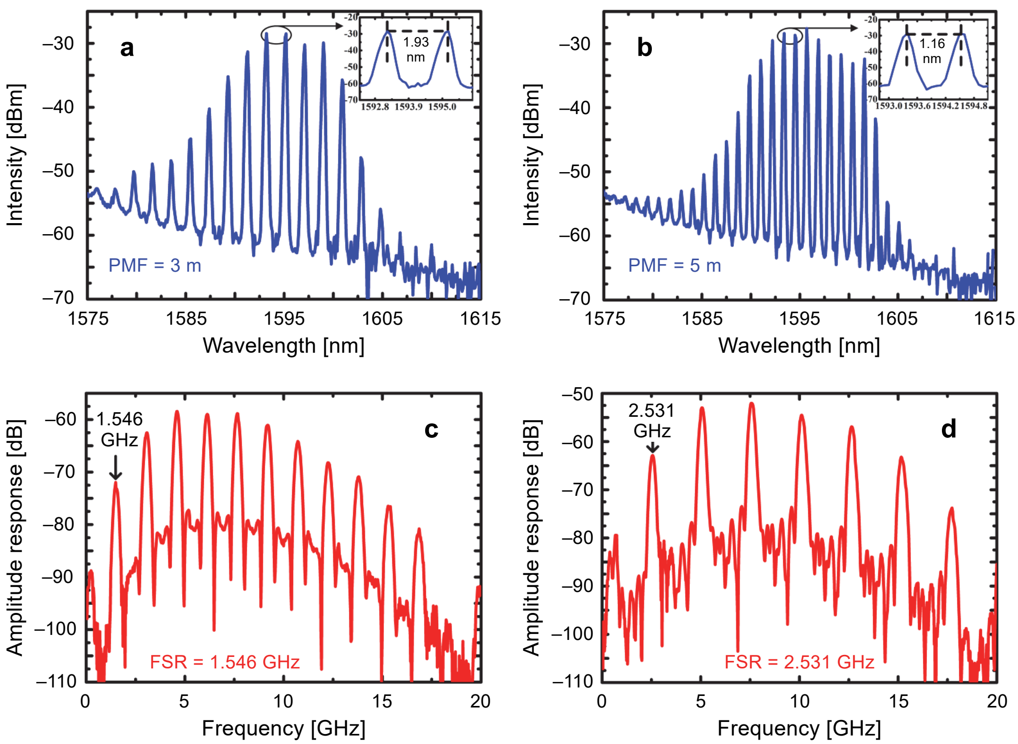

Fig. 4. Measured optical spectrums of multiple taps when the lengths of PMF are 3 m (**a**) and 5 m (**b**). The corresponding frequency responses of the multi-tap bandpass MPF (**c**, **d**). Inset – the zoom-in view of two arbitrary adjacent optical taps.

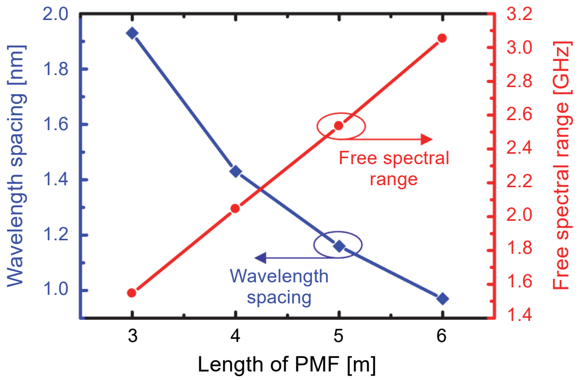

Fig. 5. Wavelength spacing of the multiple taps and FSR of the multi-tap bandpass MPF with different length of PMF.

changing the length of PMF in the Hi-Bi FLM, as discussed before. Figures 4**a** and 4**b** show the optical spectrum of multiple taps with different length of PMF. As can be seen, when the length of PMF is increased from 3 to 5 m, the wavelength spacing of multiple taps is decreased from 1.93 to 1.16 nm. The measured corresponding frequency responses are shown in Figs. 4**c** and 4**d**, from which one can see that FSRs of the multi-tap bandpass MPF are 1.546 and 2.531 GHz, respectively, which show good agreements with the theoretical values (1.560 and 2.596 GHz) calculated according to Eq. (2). When the wavelength spacing of multiple taps is altered, the shape of the MPF also alters slightly. This is mainly because as the wavelength spacing is altered, the number of multiple taps varies slightly due to different power distribution [5].

The wavelength spacing of multiple taps and the FSR can be plotted as functions of the length of PMF, as shown in Fig. 5. The blue curve represents the relationship between the wavelength spacing of multiple taps and the length of PMF. The red curve represents the relationship between the FSR and the length of PMF. For a given 2-km DCF, when the lengths of PMF are 3, 4, 5, 6 m, the wavelength spacings of the multiple taps are 1.93, 1.43, 1.16, and 0.97 nm, the corresponding FSR are 1.546, 2.045, 2.531, and 3.052 GHz, respectively. As the length of PMF increases, the wavelength spacing of multiple taps decreases, and the corresponding FSR of the proposed multi-tap bandpass MPF increases, in accordance with Eqs. (2) and (3). The tunability is discontinuous due to the discontinuous adjustment of PMF in the experiment. The tuning range would be larger as well as continuous if a polarization differential delay line (PDDL) [19] is available.

4. Conclusions

We proposed and experimentally demonstrated a reconfigurable and tunable multi-tap bandpass MPF based on a HMFRL. The HMFRL containing a hybrid gain medium and a Hi-Bi FLM serves as a stable multiple taps generator for the MPF. By adjusting the bias of the SOA from 344 to 450 mA, the number of multiple taps can be increased without OSNR degradation, and a bandpass MPF with reconfigurable bandwidth from 449 to 274 MHz is achieved. In addition, by changing the length of PMF in the Hi-Bi FLM, the wavelength spacing of multiple taps can be varied, making the multi-tap bandpass MPF's FSR tunable. The tuning range would be larger as well as continuous if a PDDL is available. The proposed reconfigurable and tunable multi-tap bandpass MPF have potential applications in optical communication system, radio-over-fiber (RoF) system, *etc*.

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