Widely tunable single bandpass microwave photonic filter based on Brillouin-assisted optical carrier recovery

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Abstract: A widely tunable single bandpass microwave photonic filter (MPF) based on Brillouin-assisted optical carrier recovery in a highly nonlinear fiber (HNLF) with only one optical filter is proposed and experimentally demonstrated. The fundamental principle lies in the fact that the suppressed optical carrier of the phase modulated optical signal could be recovered by the stimulated Brillouin scattering (SBS) amplification effect. When phase modulated optical signals go through an optical filter with a bandpass response, the optical carrier and the upper sidebands suffer from the suppression of the optical filter because they fall in the stopband of that. In our system, the optical carrier could be recovered by the SBS operation around 38 dB. The MPF is achieved by one-to-one mapping from the optical domain to the electrical domain only when one of phase modulated sidebands lies in the bandpass of the optical filter. It shows an excellent selectivity with a 3-dB bandwidth of 170 MHz over a tuning frequency range of 9.5-32.5 GHz. The out-of-band suppression of the MPF is more than 20 dB. Moreover, the MPF shows an excellent shape factor with 10-dB bandwidth of only 520 MHz. The frequency response of the MPF could be widely tuned by changing the frequency difference between the frequency of the optical carrier and the center frequency of the bandpass of the optical filter. A proof-of-concept experiment is carried out to verify the proposed approach.

OCIS codes: (060.2310) Fiber optics; (060.5625) Radio frequency photonics; (070.4340) Nonlinear optical signal processing.

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#222854 - $15.00 USD Received 10 Sep 2014; revised 5 Nov 2014; accepted 7 Nov 2014; published 17 Nov 2014
(C) 2014 OSA 1 December 2014 | Vol. 22, No. 24 | DOI:10.1364/OE.22.029304 | OPTICS EXPRESS 29304

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1. Introduction

Microwave photonic filters (MPF) have attracted considerable attention in the past few years in the field of modern radar and warfare systems because of its potentially attractive features such as light weight, low loss, wide bandwidth, large tunability, flexible reconfigurability, and immunity to electromagnetic interference (EMI) compared with microwave filters realized in the electrical domain [1–3]. Most of the previously reported MPFs are implemented based on the incoherent operation to effectively avoid the optical interference, in which only the optical intensity is manipulated. Since the intensity is always positive, only the lowpass periodic transfer function can be achieved [4]. In order to overcome this limitation, the negative coefficients should be realized to consequently obtain bandpass or highpass filters to effectively eliminate the baseband resonance of a typical lowpass filter. Up to now, the MPF with negative coefficients has been comprehensively reported [5]. However, for a given system, the frequency response of the MPF with positive or negative coefficients is usually fixed apart from adjusting the basic time delay. When the basic time delay is changed, the shape and the free spectrum range (FSR) will be inevitably changed. Therefore, the MPF with positive or negative coefficients suffers from a natural drawback of tunability. The MPF with complex coefficients is necessary which can be fully tuned without changing the shape and the bandwidth of the mainlobe and sidelobe [3, 6].

#222854 - $15.00 USD Received 10 Sep 2014; revised 5 Nov 2014; accepted 7 Nov 2014; published 17 Nov 2014

It is worth noting that the above mentioned approaches suffer from the presence of multiple harmonic bandpasss in their frequency response. Single bandpass MPFs are highly desirable for many applications which require a wide frequency rejection range to avoid spectral overlapping [7–18]. Therefore, the single bandpass MPFs are needed to meet these applications. To do so, many approaches have been reported to realize single bandpass MPFs [7–18]. The single bandpass MPF has been achieved based on a fiber Mach-Zehnder interferometer (MZI) in conjunction with an intensity modulator or a phase modulator [7, 8]. The latter can be used to suppress the baseband resonance of its periodic spectral response. However, the MZI structure is usually sensitive to the environmental disturbance. J. H. Lee proposed an alternative candidate to achieve a single bandpass frequency response based on a joint use of a digital micromirror device-based spatial light modulator and a broadband optical source [9]. However, the baseband resonance cannot be removed in this system and the proposed system is comparably complicated. The single bandpass MPFs have been also proposed by means of a pair of chirped fiber Bragg gratings (CFBG) with grating reflectivity of 50% and 100% [10], a notch ring resonator [11], a narrow bandwidth amplification effect of a SBS process achieving a phase modulation to intensity modulation conversion [12, 13], a two-dimensional liquid crystal on silicon pixel array in combination with a dual-input electro-optic modulator based on combined effects from both the dispersion-induced carrier suppression effect and the RF decay effect [14], a non-coherent broadband optical source and the variable optical carrier time shift method [15], a cascading two narrow bandwidth Bragg gratings [16]. The above mentioned approaches free from the periodic spectral response which limits the bandwidth of the microwave signal to be processed. However, in these systems, complicated structures or extra special optical components are generally required. Recently, W. Z. Li proposed a powerful method to obtain a single bandpass MPF using a phase-shifted fiber Bragg grating (PS-FBG) to achieve effective a phase-modulation to intensity-modulation conversion. Only when one of sidebands of the phase modulated optical signal falls into the notch of the PS-FBG, can a microwave signal be generated [17]. However, in the proposed method, the frequency tuning range is restricted by the bandwidth of the bandpass of the PS-FBG. Moreover, the optical carrier must be located in the bandpass of the PS-FBG to avoid that the optical carrier is suppressed. A. B. Matsko et al. proposed a powerful method to realize tunable RF photonic bandpass or bandstop filters based on high-Q optical micro-resonators [18]. The tunable RF photonic filters can be tuned in a wide frequency range and the best achieved out-of-band suppression is up to 90 dB which is a real challenge. However, the RF photonic filter requires some special high-Q optical filters and the realization of that is also difficult. Y. Deng et al. proposed another method to obtain a tunable flat-top MPF based on a multi-phase-shifted fiber Bragg grating in conjunction with a programmable optical filer to remain the optical carrier [19]. However, the programmable optical filter suffers from large insertion loss and the single bandpass MPF is achieved at the cost of increased system complexity. Moreover, two cascading optical filters have to be used in this method.

In this paper, we propose a new method to achieve a widely tunable single bandpass MPF based on Brillouin-assisted optical carrier recovery in a HNLF. The single bandpass MPF is realized with only one optical bandpass filter, for the first time to our best knowledge, based on a direct mapping from a bandpass filter in the optical domain to one in the electrical domain. The center frequency of the bandpass of the proposed MPF is equal to the frequency difference between the frequency of the optical carrier and the center frequency of the bandpass filter. When the frequency difference is changed, the center frequency of the proposed MPF will be correspondingly tuned. The bandwidth of the proposed MPF is determined by the bandwidth of the bandpass filter. When the optical carrier and sidebands go through the bandpass filter, the optical carrier and the upper sidebands are significantly suppressed by the stopband of the bandpass filter. After that, the optical carrier is recovered around 38 dB by the amplification effect of SBS operation. The proposed approach is

#222854 - $15.00 USD Received 10 Sep 2014; revised 5 Nov 2014; accepted 7 Nov 2014; published 17 Nov 2014

theoretically analyzed and experimentally demonstrated. The experimental results show that the frequency response of the single bandpass MPF is widely tunable over a frequency tuning range from 9.5 GHz to 32.5 GHz without changing its shape by simply adjusting the wavelength of the optical carrier. The 3-dB and 10-dB bandwidth are 170 MHz and 520 MHz, respectively. The out-of-band suppression is as large as 20 dB.

2. Principle

The schematic configuration of the proposed MPF based on Brillouin-assisted optical carrier recovery in a HNLF is illustrated in Fig. 1. An optical carrier from a continuously tunable laser diode (LD) with a tunable angular frequency ω_c is fiber-coupled to an optical coupler to divide into two arms by splitting ratio of 1:1. In the upper arm, the optical carrier is firstly launched into a phase modulator (PM) which is driven by a frequency-swept microwave signal generated by an electrical vector network analyzer (EVNA). Then, the phase modulated optical signal is sent into an optical filter with narrow bandwidth, which effectively removes the optical carrier and the upper sidebands to realize a carrier-suppressed single sideband (SSB) modulation. There is a frequency offset between the optical carrier and the optical filter resulting in an asymmetrical rejection of the phase modulated sidebands to achieve the SSB modulation. The carrier-suppressed optical signal is amplified by an erbium-doped fiber amplifier (EDFA) to compensate the insertion loss of the optical filter. In the lower arm, the optical carrier is fed into a frequency shifter (F-S), which consists of a polarization modulator (PolM), a polarizer (Pol), and a polarization controller (PC). The joint use of the PolM, the PC and the Pol is equivalent to an intensity modulator. The F-S is driven by a sinusoidal microwave signal with a fixed angular frequency of ω_{SBS} from a microwave source (MS). The optical carrier can therefore be up-shifted in a frequency of $\omega_{SBS} + \omega_c$. The frequency shifted optical signal acts as Brillouin pump and can be used to recover the suppressed optical carrier. Moreover, the frequency shifted optical signal can also be obtained using a dual-parallel Mach Zehnder modulator (DPMZM) in conjunction with a 90 hybrid coupler [20]. The bias of the equivalent MZM which is slightly changed by the surrounding environmentally perturbations depends on the angle of the PC in the F-S. If the bias is changed, will the power of the pump optical signal correspondingly be change. As a result, the transmission response of the MPF will be changed. Moreover, as we all know, the SBS effect is polarization dependent [21]. When the state of polarization in the lower arm is randomly rotated, the amplification effect of the SBS operation will be restrained. However, at room temperature in a laboratory environment, the frequency response of the MPF was remained when the system operates for more than 10 minutes. To this problem, a solution is that the subsystem could be individually sealed in a closed container to prevent air flow and acoustic vibrations. Meanwhile, the equivalent MZM is also replaced by a MZM with a low half-wave voltage.

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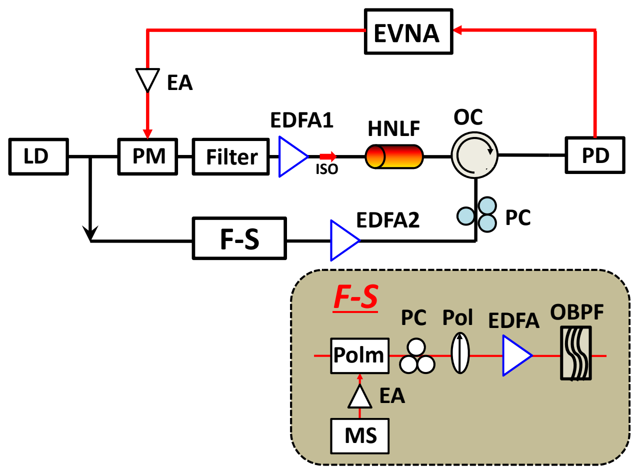

Fig. 1. Schematic diagram of the proposed single bandpass MPF (LD: laser diode; PM: phase modulator; ISO: isolator; PC: polarization controller; PD: photodetector; OBPF: optical bandpass filter; EA: electrical amplifier; F-S: frequency shifter; EDFA: erbium-doped fiber amplifier; OC: optical circulator; HNLF: highly nonlinear fiber; PolM: polarization modulator; pol: polarizer; MS: microwave source; EVNA: electrical vector network analyzer).

The frequency shifted optical signal is circulated into an opposite port of a HNLF via an optical circulator (OC) to pump the forward-propagating phase modulated optical signal. In the HNLF, the SBS process occurs between the two counter-propagated optical signals. Because the two optical signals are emitted from the same laser at the frequency of ω_c, a stable SBS operation is obtained. The frequency shifted optical signal introduces SBS gain to boost the optical carrier to achieve optical carrier recovery shown in Fig. 2(a). The SBS effect is optimized using the PC by rotated the state of polarization of the counter-clockwise propagated pump optical signal. Within the passband of the optical filter, the beating between the recovered optical carrier and the lower sideband to generate microwave signals while the corresponding upper sideband is removed by the stopband of the optical filter. Only when the selected optical sidebands lie in the passband of the optical filter attached after the PM, can phase modulation to intensity modulation conversion happen and the corresponding MPF be realized. Whereas, when the sideband of the SSB modulated signal locates out of band of the optical filter, there is no microwave signal obtained because the phase modulated sideband is effectively suppressed. In our scheme, only one optical filter is used to realize the single bandpass MPF. The SSB modulated optical signal is sent to a photodetector (PD). The sideband of the SSB modulated signal undergoes magnitude changes going through the optical filter which can be mapped to the variation of the recovered microwave signal after detected by the PD corresponding to the frequency response of the MPF shown in Fig. 2(b). The frequency response of the proposed MPF is measured by the EVNA. The central frequency of the achieved MPF is equal to the frequency difference between the center frequency of the optical filter and the frequency of the optical carrier. The MPF with a center frequency of ω_e can be widely tunable via changing the frequency of the optical carrier. Moreover, the bandwidth of the proposed MPF is determined by that of the optical filter.

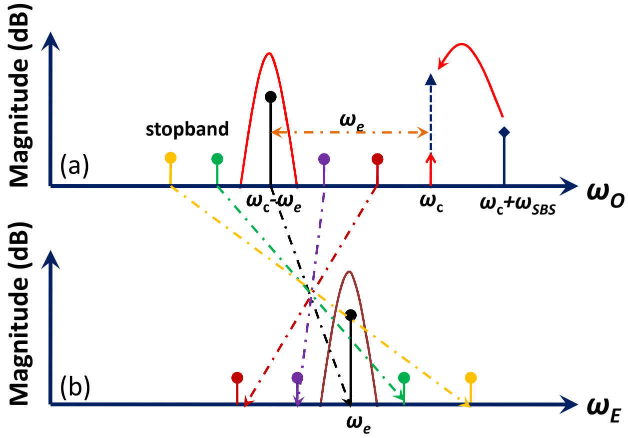

Fig. 2. Illustration of the proposed single bandpass MPF. (a) Transmission spectrum of the optical filter in the optical domain, (b) corresponding frequency response of the MPF in the electrical domain.

We consider the optical carrier injected into the PM has a normalized electrical field expressed as exp(jω_ct) where ω_c is the angular frequency of the optical carrier. The electrical field at the output of the PM can be expressed as

$$E_{PM}(t) = a_{-1} \exp j(\omega_c - \omega_e)t + a_0 \exp j\omega_c t + a_{+1} \exp j(\omega_c + \omega_e)t \tag{1}$$

where a_{-1}, a_0, and a_{+1} are the complex amplitudes of the negative first order sideband, the optical carrier, and the positive first order sideband, respectively. Under small-signal condition, only two first-order sidebands are considered in Eq. (1). ω_e is the angular frequency of the frequency-swept microwave signal from the EVNA. Applying the Fourier transform to Eq. (1) and considering the SSB modulation, the Eq. (1) can be rewritten as

$$E_{PM}(\omega) = 2\pi a_{-1}\delta\left[\omega - (\omega_c - \omega_e)\right] + 2\pi a_0 \delta(\omega - \omega_c) \tag{2}$$

After the optical filter, the optical signal can be expressed as

$$\begin{aligned} E_{filter}(\omega) &= E_{PM}(\omega)\cdot H(\omega) \\ &= 2\pi\left\{a_{-1}H(\omega_c - \omega_e)\delta\left[\omega - (\omega_c - \omega_e)\right] + a_0\beta H(\omega_c)\delta(\omega - \omega_c)\right\} \end{aligned} \tag{3}$$

where $H(\omega)$ is the magnitude response of the optical filter. β is the loss coefficient of the optical filter imposing to the optical carrier. The residual optical carrier will be boosted by the SBS gain. The SBS gain coefficient is expressed as G. When $\beta \times G>1$, the optical carrier is effectively recovered by the SBS operation. The frequency shifted optical signal acting as Brillouin pump can be expressed as follow:

$$E_{F-S}(t) = a_{+1} \exp j(\omega_c + \omega_{SBS})t \tag{4}$$

After square-law detection in the PD, we obtain the microwave photocurrent for the ω_e component as follow

$$i(\omega_e) \propto a_0 a_{-1} \beta G H(\omega_c - \omega_e) H^*(\omega_c) \tag{5}$$

As can be seen from Eq. (5), the frequency response of the proposed MPF is determined by the magnitude response of the optical filter. Therefore, we have the frequency response of the single bandpass MPF as follow:

#222854 - $15.00 USD Received 10 Sep 2014; revised 5 Nov 2014; accepted 7 Nov 2014; published 17 Nov 2014

$$H\left(\omega_c-\omega_e\right)\propto\frac{i(\omega_e)}{a_0a_{-1}\beta GH^*\left(\omega_c\right)} \tag{6}$$

In our scheme, the complex constant a_0 and a_{-1} can be obtained by a calibration operation. $H(\omega_c)$ is a constant since it is the magnitude response of the optical filter at the fixed frequency. For the given optical filter, the loss coefficient usually keeps identical. The gain coefficient G could be optimized into the maximum by simply adjusting the state of polarization and changing the optical power of the Brillouin pump optical signal [21]. As can be seen from Eq. (5), we can clearly find the phase modulated optical signal is converted to a microwave signal through phase modulation to intensity modulation conversion. The center frequency of the single bandpass MPF could be widely tuned by changing the wavelength of the optical carrier. The tuning step of the MPF is dependent on the wavelength resolution of the LD.

3. Experiment and result

We carried out an experiment to verify the proposed single bandpass MPF based on the setup shown in Fig. 1. The LD is wavelength tunable with a wavelength resolution of 1 pm in the whole C-band. In our experiment, the wavelength was firstly set at 1549.925 nm. The output power of LD was fixed at 173.4 mW. The optical carrier signal was firstly split into two arms. The PM has a bandwidth of 40 GHz and a half-wave voltage of 3 V. The PM frees from the bias-drift problem and has low insertion loss compared with the intensity modulator. The PM was driven by a microwave sinusoidal signal generated from an EVNA with a working bandwidth from 50 MHz to 40 GHz at the fixed output power of −20 dBm. An EA was inserted between the output of the EVNA and the RF port of the PM to boost the output power of the EVNA. The phase modulated optical signal was amplified by an EDFA connected after the output of the PM to amplify the optical signal at a fixed output power of 20 dBm. The amplified optical signal was injected into the optical filter and hence the optical carrier was removed by that, which has a bandpass response. In our experiment, a Fabry-perot (F-P) filter acts as the optical filter. The filtered optical signal then was sent into a HNLF via an ISO. When the pump optical signal is properly optimized by adjusting the output optical power of the EDFA2 and rotating the polarization direction of the optical signal in the lower, the SBS effect could be improved. The counter-clockwise propagating pump wave could be effectively suppressed by the ISO. The length of the HNLF is 1 km. A key structure in the lower arm was an F-S, which consisted of a PolM, a PC, a Pol and an OBPF. The PolM with a bandwith of 40 GHz and a half-wave voltage of 3.5 V was driven by a fixed frequency microwave signal from the output of a MS. The MS has a bandwidth of 20 GHz and was set at the frequency of 9.205 GHz corresponding to the Brillouin frequency shift of the HNLF. The PolM, the PC in conjunction with the Pol are equivalent to an intensity modulator, which was biased at the minimum transmission point by adjusting the PC. The frequency shifted optical signal was firstly boosted by the EDFA2 and then circulated into the opposite port of the HNLF to pump the suppressed optical carrier. The SBS operation occurred in the HNLF between the phase modulated optical signal and the frequency shifted optical signal. By simply adjusting the state of polarization of the Brillouin pump optical signal, the SBS effect can be optimized. Through the Brillouin-assisted optical carrier amplification, the optical carrier was amplified more than 38 dB. Moreover, the optical filter attached after the PM can effectively suppress the upper sidebands of the phase modulated optical signal to achieve SSB modulation. The SSB modulated optical signal was then injected into a PD with a bandwidth of ~40 GHz and a responsivity of 0.6 A/W. The EVNA connected after the PD to measure the frequency response of the proposed MPF. The center frequency of the bandpass of the MPF can be tuned by changing the wavelength of the optical carrier.

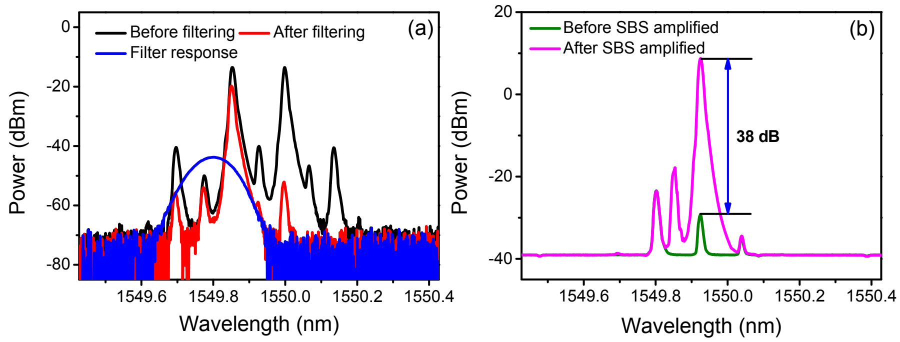

Fig. 3. Measured optical spectra of (a) the frequency shifted optical signal at the output of the F-S, (b) the optical carrier before and after amplified by the SBS gain.

The optical spectrum of the frequency shifted optical signal measured at the output of the F-S in the lower arm is shown in Fig. 3(a) in red line. The MS was operated at a CW mode with a microwave signal at 9.205 GHz and an output power of −3 dBm. The measured optical spectrum at the output of the Pol is shown in Fig. 3(a) in black line, which the optical carrier was suppressed. An OBPF with a narrow bandwidth attached after the Pol was used to select out the first order modulation sideband. After that, the undesirable optical sidebands are lower than the selected sidebands more than 33 dB. In order to demonstrate the SBS amplification effect, the frequency shifted optical signal was injected into the HNLF along the counter-clockwise direction. It is obviously observed that the suppressed optical carrier for forward-propagating could be effectively recovered more than 38 dB shown in Fig. 3(b) in magenta line. The SSB modulated signal is shown in Fig. 4(a) in black line. Figure 4(b) shows the normalized frequency response of the single bandpass MFP with a center frequency of 12 GHz and a 3-dB bandwidth of 170 MHz. As can be seen from the Fig. 4(b), we can indicate the MPF exhibits an excellent frequency resolution. The out-of-band suppression is as large as 20 dB. In addition, the MPF is of a remarkable shape factor because the 10-dB bandwidth is only 520 MHz. As can be seen in Fig. 4(b), the out-of-band noise of the MPF is crazy which is mainly attributed to the spontaneous emission of the EDFA1 and EDFA 2 and the backscattered pump optical. To this problem, an OBPF could be attached after the OC to effectively suppress the noise for improving the noise figure (NF) of the MPF. If the optical carrier signal and microwave signal with the low relative intensity noise and phase noise could be used, the NF of the MPF could also be mitigated. Moreover, the thermal and shot noise of the PD that are generally unavoidable noise sources in the optical intensity detector could be properly eliminated, which will improve the NF of the MPF. The improvement of the NF with the help of a low noise amplifier (LNA) to take the place of the EA is also feasible. The out-of-band suppression of the MPF is around 20 dB, which could be improved by optimizing the power ratio between the optical carrier and the corresponding modulation sidebands. When the power ratio reaches 1:1, the power of the recovered microwave signal is maximal. If a PD which can accept larger input optical power could be employed, the out-of-band suppression of the MPF is also enhanced. The proposed single bandpass MPF scheme could also be used to spectrally characterize the transmission response of optical components with high resolution in terms of the magnitude and phase response. The proposed single bandpass MPF is equivalent to an optical vector network analyzer (OVNA) which is quite suitable to characterize the transmission response of the optical component with bandpass response. The OVNA has been proposed to characterize the transmission response of an optical component with bandpass response based on SSB modulation and segmental measurements [22]. However, the measurement of the transmission response is especially complicated because the full transmission response can be finally obtained by overlapping transmission responses of the adjacent segments. Another possible solution is based on splitting the optical carrier and sideband into two paths [23]. However, the key limitation of this method is that the phase response of the optical component is hard to be measured.

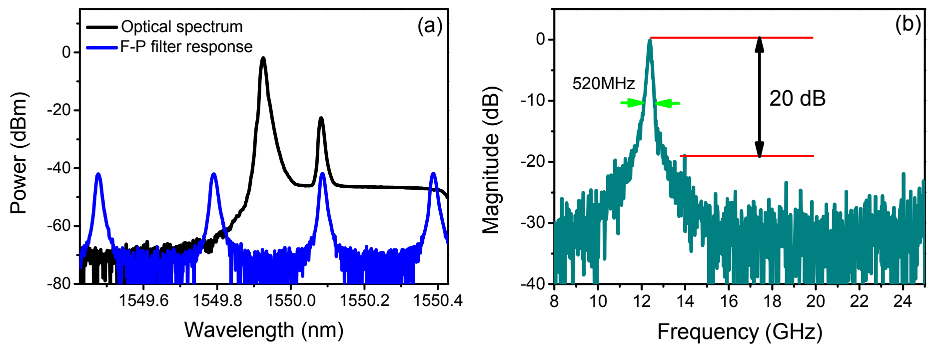

Fig. 4. (a) Measured optical spectra of optical single sideband modulated optical signals as well as the filter response of the F-P filter in blue lines, (b) measured frequency response of the single bandpass MPF with a center frequency of 12 GHz.

Figure 5 shows the measured frequency responses of the proposed single bandpass MPF with the center frequency tuning range from 9.5 GHz to 32.5 GHz. The tuning step of the MPF is mainly determined by the wavelength resolution of the LD. In our experiment, the wavelength resolution of the LD is about 1pm corresponding to a tuning step of 125 MHz. It is observed that the shape of the bandpass is slightly changed when the center frequency was tuned which is attribute to the higher order dispersion of the HNLF [24]. The proposed MPF achieve a single bandpass with an excellent out-of-band suppression when the MPF was tuned over a wide range. The upper limit of the tuning range of the single bandpass MPF is only restricted by the modulation bandwidth of the PM and the working bandwidth of the PD and the EVNA. If the working bandwidth of that could be improved, the tuning range of the single bandpass MPF can be corresponding extended. Moreover, if the 3-dB bandwidth of the optical filter can be continuously changed by an electrically controlled servo, can that of the corresponding single bandpass MPF be continuously adjusted.

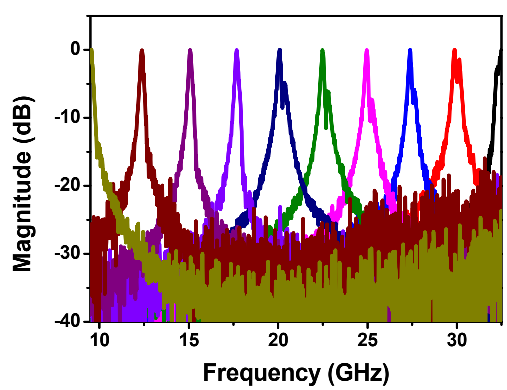

Fig. 5. Measured frequency responses of the widely tunable single bandpass MPF.

4. Conclusion

We have proposed and experimentally demonstrated a widely tunable single bandpass MPF based on Brillouin-assisted optical carrier recovery in a highly nonlinear fiber (HNLF) with only one optical filter. The proposed single bandpass MPF, for the first time to our best knowledge, obtains the widest frequency tuning range and could be realized by the direct mapping from the bandpass filter in the optical domain to that in the electrical domain

#222854 - $15.00 USD Received 10 Sep 2014; revised 5 Nov 2014; accepted 7 Nov 2014; published 17 Nov 2014

without segmental measurements. The optical filter removes the optical carrier and the upper sidebands to achieve the carrier-suppressed SSB modulation. The suppressed optical carrier could be recovered by the SBS amplification effect. The SBS operation occurs between two counter-propagated optical signals which are the phase modulated optical signal for forward-propagating and the frequency shifted optical signal, respectively. By optical carrier recovery, the suppressed optical carrier can be recovered more than 38 dB. The single bandpass MPF has been successfully realized over a frequency tuning range from 9.5 GHz to 32.5 GHz with a 3-dB and 10 dB bandwidth of only 170 MHz and 520 MHz, respectively. The out-of-band suppression is as large as 20 dB.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under 61377069, 61108002, and 61275078.