Ideal Rectangular Microwave Photonic Filter with High Selectivity Based on Stimulated Brillouin Scattering

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Abstract: We have demonstrated an ideal rectangular microwave photonic filter with flexible tenability on bandwidth, central frequency and selectivity. The 20-dB shape factor is 1.056, which is the best for microwave photonic filters in ~GHz bandwidth.

OCIS codes: (060.5625) Radio frequency photonics; (290.5900) Scattering, stimulated Brillouin

1. Introduction

In radio-frequency (RF) systems, there have been continuously interests to use photonic devices to implement flexible signal filtering function, which can be generally named as microwave photonic filter (MPF). An ideal MPF should have a single passband with flexible tenability on bandwidth, central frequency and selectivity. Most importantly, the MPF should have rectangular response with flat-top and sharp roll-off to select the desired microwave signals with high rejection of the out-of-band signals. MPFs have been generally realized by RF signal modulated single-frequency optical source followed by delayed tap filter [1] or RF signal modulated multi-wavelength optical source followed by dispersion element [2]. Optical comb has also been proposed to improve the tap numbers for enhanced filter configurability [3]. But ideal rectangular MPF with flexible tenability is extremely challenging. On the other hand, narrowband optical filter is a good candidate for MPF by mapping the microwave signals to the optical field then processing the signal in optical domain finally converting back to the microwave domain. Programmable optical processor based on liquid crystal on silicon (LCOS) [4] and virtually imaged phased-array (VIPA) [5] have been proposed to achieve narrowband flat-top MPF, but limited by the spectral resolution, ideal rectangular filter in ~GHz region cannot be achieved.

Stimulated Brillouin scattering (SBS) in fiber can be considered as an active optical filter with a spectral resolution of ~30 MHz, therefore it is a perfect choice for MPF. Recently, we have achieved a rectangular optical filter with bandwidth tuning from 50 MHz to 4 GHz by shaping the SBS pump with digitally-controlled electrical multi-tone [6]. But electrical/optical nonlinearities originated from the multi-tone pumps generate undesired out-of-band gain meanwhile pump depletion limits the maximal signal gain therefore limiting the filter selectivity to around 25 dB at 1-GHz bandwidth. Y. Stern et al. have proposed to sweep the Brillouin pump frequency combined with the polarization pulling effect in SBS process, improving the filter selectivity to around 40 dB for a 1-GHz bandwidth [7]. But the passband ripple is as high as 5 dB due to the non-flat frequency response from both electrical and optical components and the 20-dB shape factor (SF_{20dB}), defined as the ratio between the 20-dB bandwidth and 3-dB bandwidth, is between 1.35 to 1.5, which is far from the ideal case.

In this manuscript, we implement feedback control to compensate the non-flat frequency response in the pump sweeping scheme, reduce the passband ripple to less than 1.4 dB for the bandwidth from 500 MHz to 3 GHz. Then by using pump-splitting dual-stage configuration to avoid pump depletion, the selectivity is improved to 45 dB for 2-GHz bandwidth. The SF_{20dB} is 1.056 at 1-GHz bandwidth, which is almost close to the ideal rectangular case, and is the best value among all the MPFs in ~GHz bandwidth region, to the best of our knowledge. The flexible tuning of bandwidth, central frequency and selectivity is also demonstrated, showing the powerful capability of our proposed MPF.

2. Principle

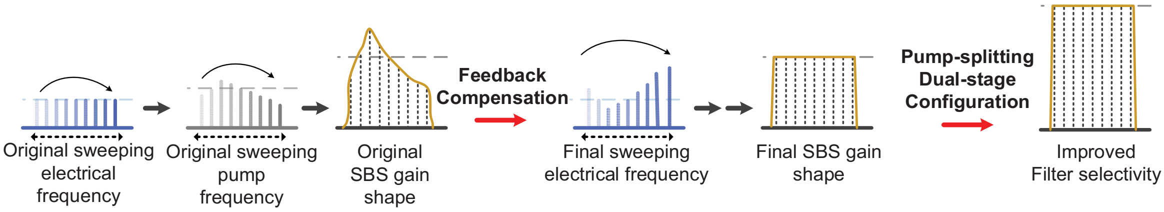

Fig. 1. Principle for achieving high selective rectangular optical filter

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The feedback compensation principle is similar as we have proposed for multi-tone pump case [6]. Here we demonstrate the feedback compensation algorithm is also applicable for pump sweeping case. Different with the multi-tone pump case where all the tones simultaneously exist, for the pump sweeping case there is only a single frequency at any specific time therefore no nonlinearities induced gain ripple and undesired out-of-band gain exist, which ensures the sharpness of the gain filter. The non-flat frequency response mainly comes from the electrical and optical components such as the digital-analog-converter (DAC), electrical driver and optical modulator. The frequency sweeping time is a key parameter to achieve a flat response after feedback compensation. Fast sweeping in ~ns duration will make the feedback algorithm fails. Slow sweeping in ~us duration can achieve very flat response but the sweeping duration should shorter than the signal propagation time in the fiber therefore the signal wave is subjected to SBS amplification by the entire sweeping pump spectrum. Besides, the pump-splitting dual-stage SBS configuration can avoid the pump depletion therefore improve the on-off SBS gain and the filter selectivity.

3. Experimental setup

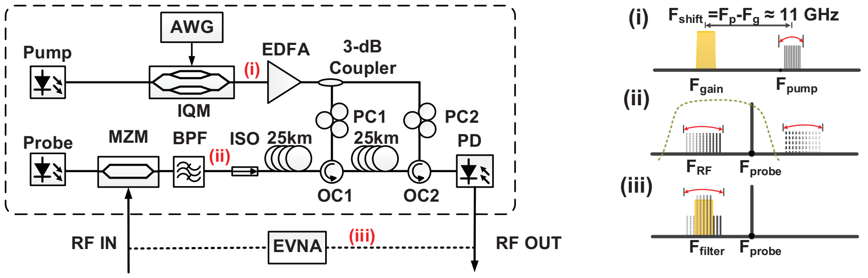

Fig. 2 Experimental setup for rectangular MPF

The experimental setup is shown in Fig. 2. Two laser sources serve as the Brillouin pump and probe respectively. In the pump branch, an arbitrary waveform generator (AWG) is used to generate the frequency sweeping signal. Then it is modulated on the light to generate the optical carrier-suppression single-sideband (OCS-SSB) SBS pump using an I&Q modulator (IQM). The OCS-SSB signal is amplified by a high power erbium-doped fiber amplifier (EDFA) and then split into two parts equally, which are launched into 25-km single mode fiber (SMF) via optical circulators (OCs). The polarization controllers (PCs) are used to achieve the maximum SBS gain. In the probe branch, the RF signal is modulated on another laser source by a standard Mach-Zenhder modulator (MZM) with double-side modulation, and a bandpass filter (BPF) is followed to suppress one sideband for SSB generation. An IQM can also be used for SSB generation same as the pump branch. An isolator (ISO) followed by the BFP is used to prevent the residual pump power from the BPF and MZM. The probe light goes through the fiber and its sideband is amplified once it falls into the SBS gain region. The processed RF signal is detected using a photodiode (PD) by beating the probe carrier and the amplified sideband. The amplitude and phase response of the SBS based MPF are measured by an electrical vector network analyzer (EVNA). The waveform generated by AWG, the pump wavelength and the pump power determine the shape, central frequency and selectivity of the filter, respectively. In the experiment, we fix the frequency sweeping duration at 1 us, which can achieve effective feedback compensation and is also much shorter than the propagation time of ~ 120 us in 25-km SMF.

4. Experimental results

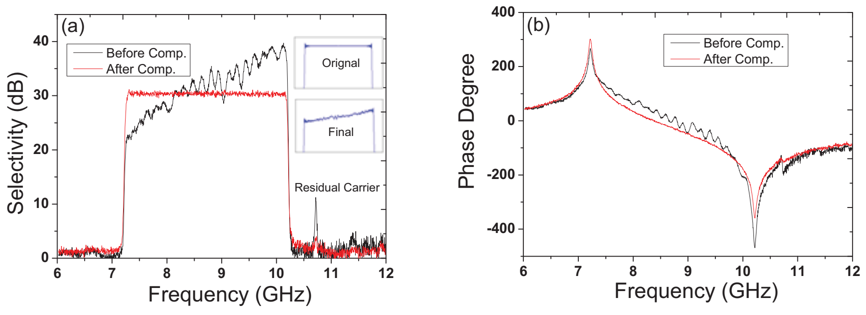

Fig.3 Filter amplitude and phase response before and after feedback compensation

Firstly we show the effectiveness of the feedback compensation for a 3-GHz filter. With a very flat sweeping pump signal as shown in the inset of Fig. 3 (a), the passband ripple is as high as 15 dB due to the bandwidth limitation of the AWG and the non-flat frequency response of the electrical and optical components, where the low-frequency SBS gain corresponds to the high-frequency pump. The carrier of the pump cannot be fully suppressed therefore generating a peak outside the filter passband. After implementing the feedback compensation, the passband ripple is reduced to +/- 0.7dB and the pump carrier is also fully suppressed. Pre-compensation of the pump waveform can also optimize the passband ripple to some extent, but only feedback compensation can fully suppress the ripples and achieve a smooth gain response. Unlike the multi-tone pump case, there is no nonlinearity-induced out-of-band gain therefore the filter selectivity is equal to the on-off SBS gain. The phase response of the filter before and after feedback compensation is also shown in Fig. 3 (b). Note that once the feedback compensation is completed, the pump waveform will be stored in the memory for future use with long-term stability.

By changing the bandwidth of the sweeping pump signal, the filter bandwidth can be tuned from 500 MHz to 3 GHz while keeping the passband ripple less than +/- 0.7dB as shown in Fig. 4 (a). The corresponding phase response of the filters are shown in Fig. 4 (b). By tuning the pump wavelength, the central frequency of the filter can be flexibly tuned while the rectangular shape still keeps unchanged. Simultaneously, the filter bandwidth can be tuned by modifying the pump waveform stored in the memory as shown in Fig. 4(c).

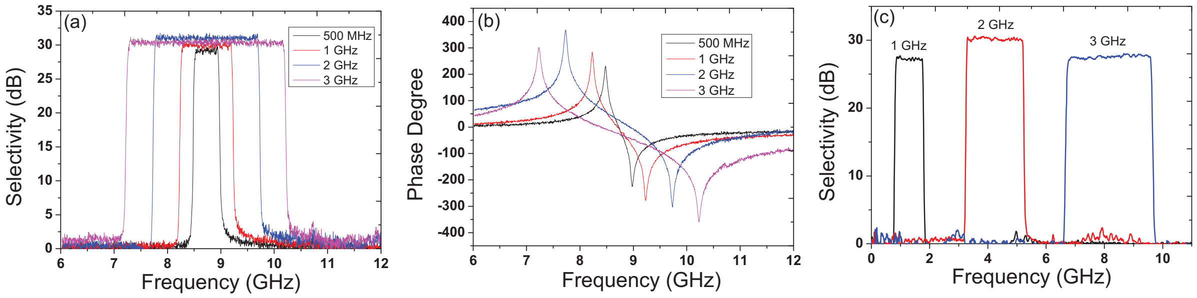

Fig. 4 Filter bandwidth and central frequency tuning and the corresponding phase response

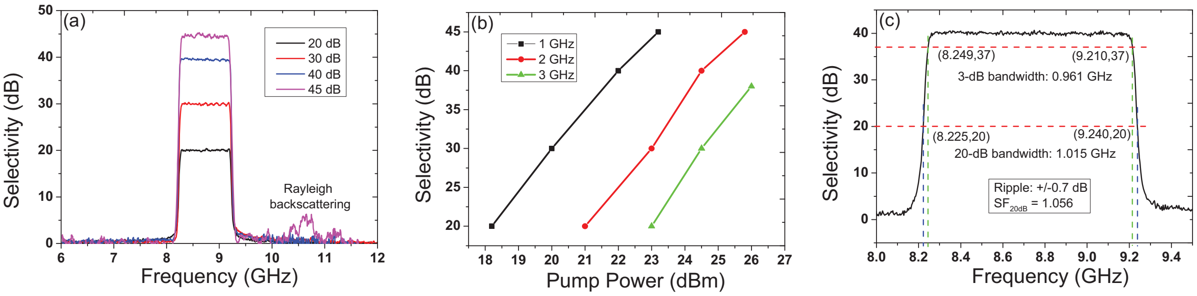

Fig. 5 Filter selectivity tuning, selectivity variation with pump power and the shape factor measurement

The filter selectivity can be tuned by simply changing the pump power with the same pump waveform. Take a 1-GHz rectangular filter as an example, the selectivity can be increased from 20 dB to 45 dB by increasing the pump power from 18.2 dBm to 23.2 dBm, while keeping the ideal rectangular shape as shown in Fig. 5 (a). Actually the on-off SBS gain is as high as 55 dB at 23.2 dBm pump power but the measured selectivity of 45 dB is limited by the dynamic range of the PD. The small ripple in 10-11 GHz region origins from the beating between the amplified probe and the pump Rayleigh backscattering. With the increase of the filter bandwidth, the required pump power is higher. But compared with the single-pump single-stage configuration, the required pump power will be much lower. Finally, we measure the shape factor for a 1-GHz filter with 40-dB selectivity, the SF_{20dB} is 1.056, which is the best value among all the MPFs in ~GHz bandwidth region, to the best of our knowledge.

4. Conclusion

We have demonstrated a high selectivity rectangular MPF based on SBS effect in optical fiber. By using pump sweeping scheme combined with feedback compensation and pump-splitting dual-stage configuration, an ideal rectangular filter with as high as 45-dB selectivity was achieved. The flexible tuning of bandwidth, central frequency and selectivity shows the powerful capability of the proposed SBS-based MPF. The polarization independent operation of this MPF is the next objective of this work.

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