Polarization-Independent Rectangular Microwave Photonic Filter Based on Stimulated Brillouin Scattering

Lilin Yi, Wei Wei, Yves Jaouën, Mengyue Shi, Bing Han, Michel Morvan, and Weisheng Hu

(Top-Scoring Paper)

***Abstract*—We have demonstrated a rectangular microwave photonic filter (MPF) based on stimulated Brillouin scattering (SBS) effect in optical fiber and offering tunability on bandwidth, central frequency, and selectivity. A sweeping-pump multistage configuration with feedback control is implemented to achieve the rectangular MPF with high selectivity. The obtained 20-dB shape factor is as low as 1.056, which is, to our knowledge, the best reported result for MPF in gigahertz bandwidth. Furthermore, we solve the polarization-dependent SBS gain issue and realize a polarization-independent MPF. The SBS noise is reduced by adopting a multistage configuration to limit the gain at each stage. Finally, the filter selectivity for a four-stage configuration is as high as 57 dB for a 2.1-GHz bandwidth. In this case, the signal-to-noise ratio penalty is only 2.6 dB for a 4-Gbit/s orthogonal frequency division multiplexing signal in the quadrature-phase-shifted keying format.**

***Index Terms*—Microwave photonics filter, polarization-independent, stimulated Brillouin scattering.**

I. Introduction

In radio-frequency (RF) systems, there has been considerable interest in using photonic devices to implement flexible signal filtering functions, which are generally called microwave photonic filters (MPF). A desired MPF should have a single pass band with flexible tunability on bandwidth, central frequency and selectivity, and polarization-independent characteristics. Most importantly, the MPF should have flat-top response and high roll-off to select the desired signals with high rejection of out-of-band signals. Meanwhile, the filter should cause minimal degradation on the signal performance.

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There have been numerous publications about MPF [1]–[4], but meeting the above requirements simultaneously is extremely difficult. MPFs have generally been realized either by RF signal modulated single-frequency optical source followed by delayed tap filters [1] or by RF signal modulated multi-wavelength optical source followed by dispersion elements [5]. Optical comb has also been proposed to improve the tap numbers for enhanced filter configurability [6]. But ideal rectangular MPF with flexible tunability is extremely challenging. On the other hand, narrowband optical filter provides a good candidate for MPF by mapping the microwave signals to the optical field, then processing the signal in optical domain and finally converting it back to the microwave domain. Programmable optical processor based on liquid crystal on silicon (LCOS) [7] and virtually imaged phased-array (VIPA) [8] have been proposed to achieve narrowband flat-top MPF, but rectangular response in $\sim$GHz range cannot be achieved due to the limited spectral resolution.

Stimulated Brillouin scattering (SBS) in fiber can be considered as an active optical filter with a spectral resolution of $\sim$20 MHz; therefore, it is a perfect choice for MPF [9]–[12]. The filter bandwidth and the shape can be flexibly changed by controlling the pump spectrum using external modulation [13], [14], direct current modulation [15], [16] and cascaded phase and intensity modulation [17]. In addition, the filter extinction ratio can be increased by the polarization characteristics of the SBS amplification [14], [16]. However, as it is very difficult to precisely control the pump spectrum, the exact flat top and steep edges for the ideal rectangular filter can hardly be achieved. Recently, we have demonstrated a rectangular optical filter with bandwidth tuning from 50 MHz to 4 GHz by shaping the SBS pump with digitally-controlled electrical multi-tone algorithm with feedback compensation [18]. But electrical/optical nonlinearities originated from the multi-tone pumps generate undesired out-of-band gain. Furthermore, pump depletion limits the maximal signal gain thereby limiting the filter selectivity to around 25 dB at 1 GHz bandwidth. By using pump-splitting dual-stage configuration, the gain saturation effect can be suppressed at each stage. Pump efficiency is thus improved, and the filter selectivity can then be improved to 40 dB at 1 GHz bandwidth [19]. Apart from the multi-tone pump scheme, Y. Stern *et al.* have proposed to sweep the Brillouin pump frequency combined with the polarization pulling effect in the SBS process, also improving the filter selectivity to around 40 dB for a 1 GHz bandwidth [14]. But the pass band ripple is as high

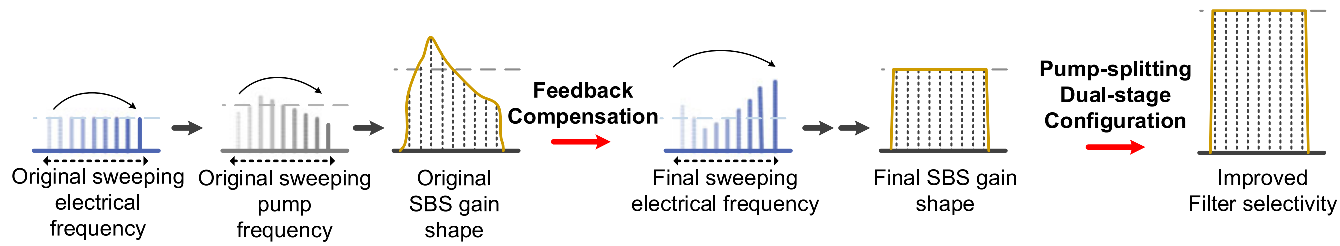

Fig. 1. Principle for achieving high selective rectangular SBS filter.

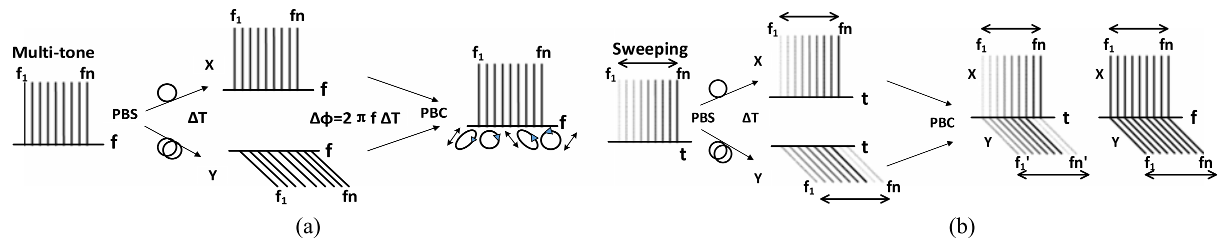

Fig. 2. Principle of achieving spectral depolarization for multi-tone pump (a) and frequency-sweeping pump (b).

as 5 dB due to the non-flat frequency response of both electrical and optical components. Recently, we have proposed a feedback control technique to compensate the non-flat frequency response in the pump sweeping scheme, and then reducing the pass band ripple to less than 1.4 dB for bandwidths ranging from 500 MHz to 3 GHz [20]. Then, by using pump-splitting dual-stage configuration to avoid pump depletion, the selectivity is improved to 45 dB for 2 GHz bandwidth. The 20 dB shape factor (SF_{20dB}) is 1.056 at 1 GHz bandwidth, which is close to the ideal rectangular case, and is, to our knowledge, the best reported value among all the MPFs in ∼GHz bandwidth range. The tuning of bandwidth, central frequency and selectivity has also been demonstrated, showing the capability and versatility of our proposed MPF.

However, two major issues still remain: first, polarization-dependent SBS gain and second, high noise contribution resulting in signal degradation. To achieve high SBS gain, and thereby, high filter selectivity, the amplifier has to operate at small input signal condition (−30 dBm in Ref. [20]). In this case, the SBS amplified spontaneous emission (SBS-ASE) is very strong; therefore, the filter will significantly degrade the signal performance. To mitigate SBS-ASE, the amplifier must operate at near saturation region, which significantly limits the signal gain and therefore, the filter selectivity. To resolve the contradiction, we propose using a pump-splitting multi-stage configuration allowing a limited single-stage gain for lower SBS-ASE while achieving a high cascaded gain for high filter selectivity. On the other hand, as SBS process is polarization-dependent, polarization state optimization is required at each stage, which makes the cascaded SBS-based MPF very complex for practical applications. Thus we propose using a depolarized frequency-sweeping pump which, for the first time, allows eliminating the polarization-dependent characteristics of the SBS-based MPF. We assess the MPF system performance by filtering a ∼4 Gbit/s orthogonal frequency division multiplexing (OFDM) signal in quadrature phase shifted keying (QPSK) format. The polarization-independent rectangular SBS filter is set to 2.1 GHz bandwidth and achieves 57 dB selectivity with only 2.6 dB signal-to-noise ratio (SNR) penalty. With these superior performances, the SBS-based filter is close to meeting all the technical requirements of the desired MPF.

The structure of this paper is as follows: In Section II, on account of previous processes, we apply the feedback compensation technique to the pump sweeping case, and then explain the necessity and principle of polarization-independent SBS operation. In Section III, we present the experimental setup for the rectangular MPF based on pump sweeping scheme along with the polarization-independent process in detail. In Section IV, we analyze the high selectivity, tunability, and low noise performance with the polarization-independent characteristic of the SBS-based MPF. Finally, in Section V, we conclude the results of the experiments.

II. Principle

Since the SBS gain increases exponentially with the pump power, even small pump power variations result in great gain differences. Thus we propose a precise control of each pump line, called feedback compensation, to realize the flat top MPF. The feedback compensation principle is similar to what we have proposed in the multi-tone pump configuration [6]. The feedback compensation algorithm is also applicable for pump sweeping case as shown in Fig. 1. The pump wave is obtained through optical carrier-suppression single-sideband (OCS-SSB) modulation driven by frequency-sweeping signal from an arbitrary waveform generator (AWG). The corresponding SBS gain is measured by an electrical vector network analyzer (EVNA). Unlike the multi-tone pump case where all the tones exist simultaneously, there is a single frequency at any specific time in the pump sweeping case. So, there is neither the nonlinearities-induced gain ripple nor the undesired out-of-band gain, thereby ensuring the sharpness of the gain filter. The non-flat frequency

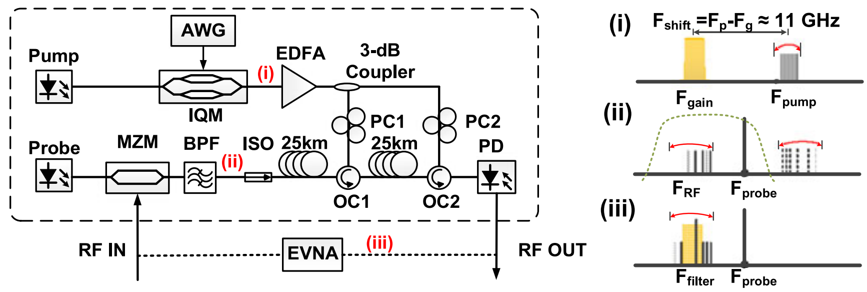

Fig. 3. Experimental setup for rectangular MPF.

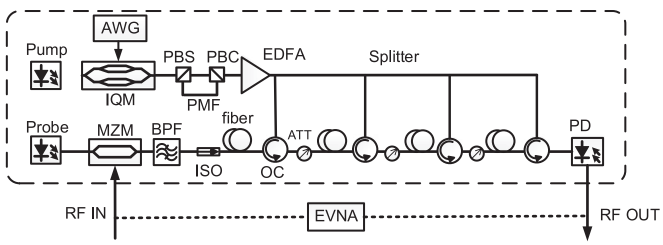

Fig. 4. Experimental setup for polarization-independent MPF based on pump-splitting four-stage SBS.

response mainly originates from the electrical and optical components such as the digital-to-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 period will make the feedback algorithm fail. Slow sweeping in $\sim\mu$s period can achieve very flat response, but the sweeping period should be shorter than the signal propagation time in the fiber; therefore, the signal wave is subjected to SBS amplification by the entire pump spectrum. Besides, the pump-splitting multi-stage configuration can avoid pump depletion.

Nevertheless, the polarization-dependent SBS characteristic necessitates a complicated control of the polarization state at each stage. Therefore, it should be desirable to eliminate the polarization-dependency of the SBS effect itself. We then propose a polarization-independent operation using a completely depolarized pump wave with a degree of polarization (DOP) near 0. This depolarization is achieved using a polarization beam splitter (PBS) to separate the broadband pump into two polarization orthogonal waves, which are then combined by a polarization beam combiner (PBC) after experiencing different fiber-based delay lines. For the multi-tone based broadband pump, the phase difference varies linearly with the frequency for the same delay. So the phase difference on two polarization projections results in a polarization state variation of each spectral line as shown in Fig. 2(a), corresponding to a spectral-averaged DOP of 0. Therefore, the depolarized multi-tone pump cannot achieve polarization-independent SBS operation and results in strong SBS gain ripple.

Unlike the multi-tone configuration where all the frequencies exist simultaneously, there is a single frequency at a time in the frequency-sweeping case. When the two delayed polarization projections are combined, the frequencies on the two polarization projections are different at any specific time; therefore, no polarization rotation happens and the pump frequency sweeps on two independent orthogonal polarization states as shown in Fig. 2(b). In the frequency domain, the depolarized frequency-sweeping pump can be considered as a broadband polarization-multiplexed pump; therefore, the polarization dependent gain (PDG) can be completely eliminated.

III. Experimental Setup

A. Rectangular MPF

In this section, we verify the above analysis experimentally. According to the pump sweeping principle, we set up the experiment for the rectangular MPF as shown in Fig. 3. Two laser sources serve as the Brillouin pump and the probe respectively. In the pump branch, an AWG is used to generate the frequency sweeping signal. Then it is modulated in the light to generate the SBS pump with OCS-SSB modulation using an I&Q modulator (IQM). The OCS-SSB pump light is then amplified by a high power erbium-doped fiber amplifier (EDFA) and split equally into two parts, which are finally launched into 25-km single mode fiber (SMF) spools via optical circulators (OCs). Polarization controllers (PCs) are used to achieve the maximum SBS gain. In the probe branch, another laser source is amplitude modulated by a standard Mach-Zehnder modulator (MZM) with RF signal. An optical bandpass filter (BPF) with a 3 dB bandwidth of 10 GHz is used to suppress one sideband and obtain SSB format. Note that an IQM can also be used for SSB generation as in the pump branch. The probe light is launched into 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 EVNA. The waveform generated by the 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 μs, which can achieve effective feedback compensation and is also much shorter than the propagation time of ∼120 μs in the 25-km SMF. Note that the pump sweeping time of 1 μs is much longer than the lifetime of the SBS phonons of around 10 ns. The SBS interaction for different parts of the spectrum takes place at different spots in the fiber thereby reducing the effective length of the SBS interaction and increasing the required

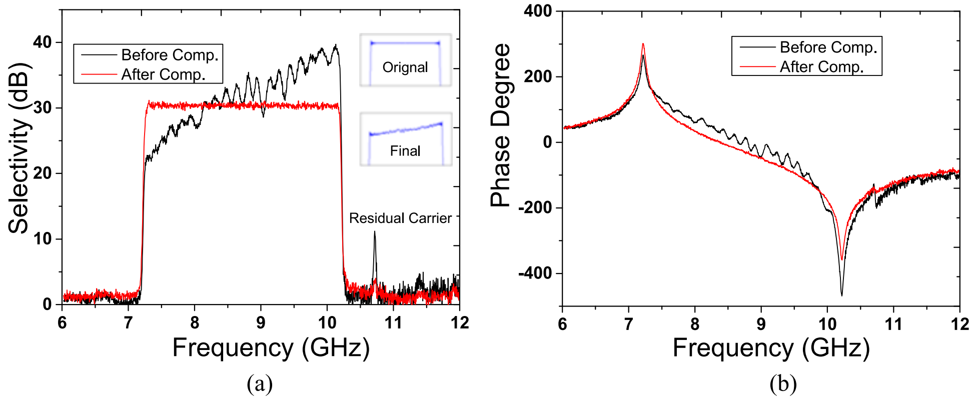

Fig. 5. Filter amplitude and phase response before and after feedback compensation.

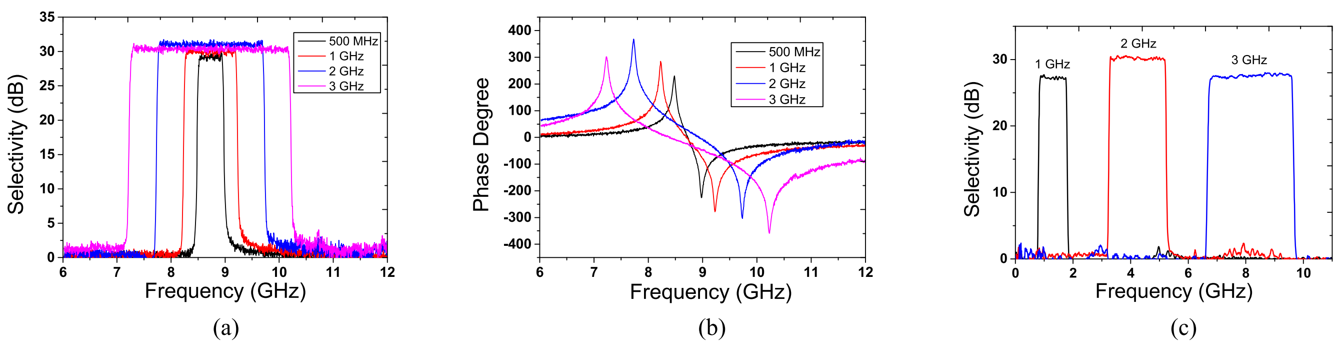

Fig. 6. Filter bandwidth and central frequency tuning and the corresponding phase response.

pump power compared with the single frequency pump case. Besides, the SBS frequency shift of a fiber depends on the fabrication and can be different at different spots of the same fiber. The temperature and strain variation on the fiber will also change the frequency shift, but the induced frequency shift variations are only in the ∼MHz region and would not significantly affect the performance of SBS-based MPF with ∼GHz bandwidth.

B. Low Noise Polarization-Independent MPF

On the basis of the rectangular MPF presented above, we can now design the low noise polarization-independent MPF. The experimental setup is shown in Fig. 4. The generation of both frequency-sweeping Brillouin pump and probe signal is the same as in the previous experiment. The broadband pump is depolarized using a PBS, a 3-m polarization maintaining fiber (PMF) and a PBC. It is then amplified by a high power EDFA and split into four equal parts, which are launched into 25-km SMF fiber sections via OCs. Note that the fiber length has not been optimized in the experiment. No polarization controllers are required for the depolarized frequency-sweeping pump scheme, which simplifies the experimental setup significantly. The probe light goes through the fiber and its sideband is amplified once it falls into the SBS gain region. The optical attenuator (ATT) at the input of the next stage is used to optimize the input power at each stage to achieve high gain and mitigate SBS-ASE. The amplitude and phase response of the SBS based MPF are measured by the EVNA. Feedback compensation algorithm is also implemented to achieve a rectangular filter response. Filter response and system performance are evaluated in the following section.

IV. Experimental Results and Performance Evaluation

A. Tunable Rectangular MPF

In this part, we show the effectiveness of the pump sweeping case with feedback compensation for a 3 GHz filter. With a very flat sweeping pump signal as shown in the inset of Fig. 5(a), the passband ripple is as high as 15 dB due to the non-flat frequency response of the electrical and optical components, where the low-frequency SBS gain corresponds to the high-frequency pump. The peak outside the filter pass band corresponds to the residual carrier of the pump. After implementing the feedback compensation scheme, the pass band ripple is reduced to ±0.7 dB and the pump carrier is fully suppressed. Pre-compensation of the pump waveform can also optimize the pass band ripple to some extent, but only feedback compensation can fully suppress the ripples and achieve a smooth gain response. Unlike the multi-tone pump scheme, there is no nonlinearity-induced out-of-band gain; therefore, the filter selectivity is equal to the on-off SBS gain, defined as the probe amplitude difference with and without the Brillouin pump power. The phase response of the filter before and after feedback compensation is shown in

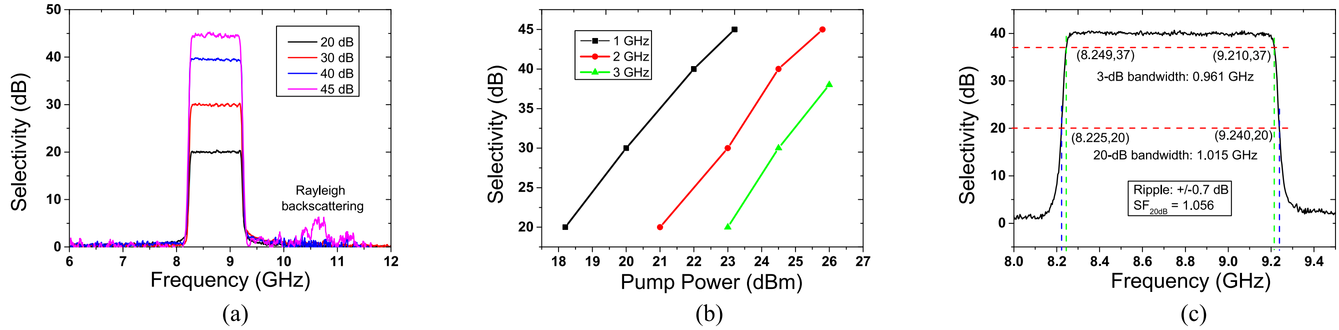

Fig. 7. Filter selectivity tuning, selectivity variation with pump power and the shape factor measurement.

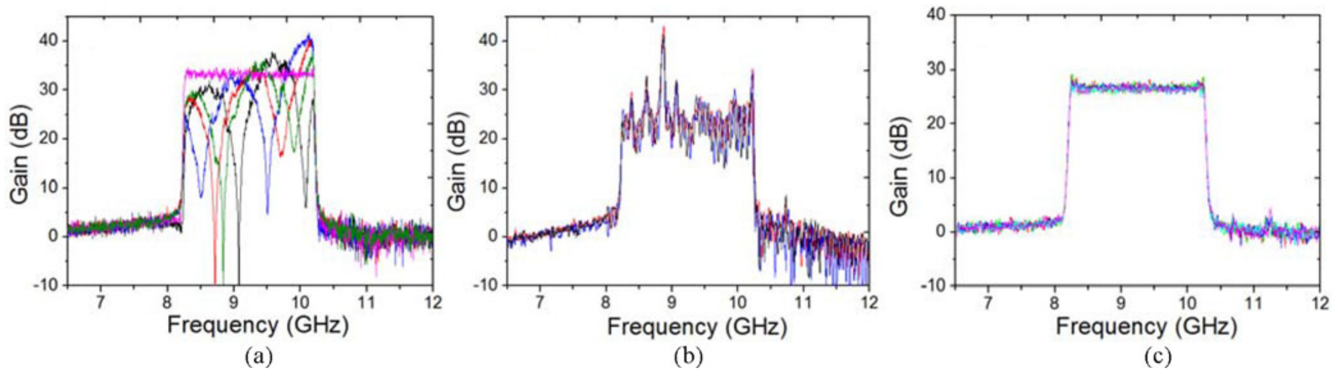

Fig. 8. The SBS gain spectra variation for different signal polarization states: (a) single-polarization pump, (b) depolarized multi-tone pump, (c) depolarized frequency-sweeping pump.

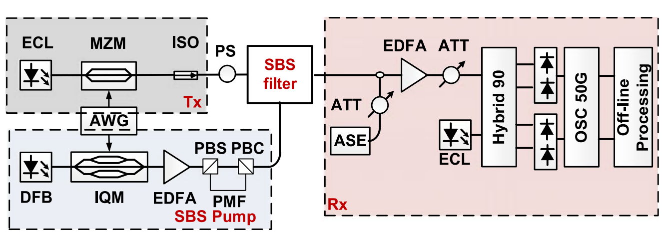

Fig. 9. The system performance evaluation setup of the polarization-independent four-stage SBS filter.

Fig. 5(b). Note that once feedback compensation is completed, the electrical pump waveform is stored for future use.

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 ± 0.7 dB as shown in Fig. 6(a). The corresponding phase response is presented in Fig. 6(b). By tuning the pump wavelength, the central frequency of the filter can be tuned while the rectangular shape remains unchanged. Simultaneously, the filter bandwidth can be tuned by modifying the electrical pump waveform stored in memory as shown in Fig. 6(c).

The filter selectivity can be tuned by simply changing the pump power with the same pump waveform. Taking 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 rectangular shape as shown in Fig. 7(a). Actually the on-off SBS gain is as high as 55 dB with 23.2 dBm pump power; however, the measurement of the selectivity is limited by the 45 dB dynamic range of the PD. The small ripple in the 10–11 GHz region originates from the beating of the amplified probe and the Rayleigh backscattering of the pump wave. With the increase in the filter bandwidth, the required pump power is higher. However, the required pump power is much lower compared to what is needed in the single-pump single-stage configuration. Finally, a shape factor (SF_{20dB}) of 1.056 for a 1 GHz filter with 40 dB selectivity is measured. This is, to our knowledge, the best result among all the MPFs in ~GHz bandwidth region.

B. Low Noise Polarization-Independent MPF

The previous experiment produces an MPF with high selectivity and flexible tunability. In this part, we propose a solution to solve the polarization dependency problem of SBS gain for superior performance. System performance is evaluated at the same time. For the single-polarization pump, the rectangular filter response optimized from a specific polarization state is completely reshaped for other polarization states due to SBS-PDG, as shown in Fig. 8(a). The filter ripple is more than 20 dB for the depolarized multi-tone pump as shown in Fig. 8(b). The filter can keep the rectangular response for different polarization states only for the depolarized frequency-sweeping pump. The PDG is less than 1 dB, as shown in Fig. 8(c), proving the polarization-independent characteristic of the SBS-based MPF

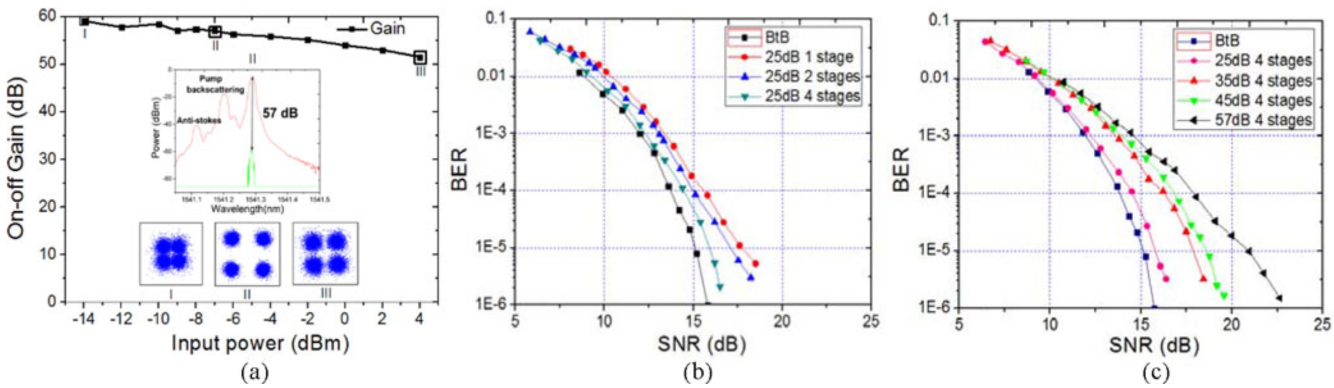

Fig. 10. (a) SBS gain and corresponding QPSK constellation variation with input power, (b) BER-SNR evolution for 25 dB signal gain with different stages, (c) BER-SNR evolution for four-stage filter with different gains.

using depolarized frequency-sweeping pump. By increasing the pump power, the filter selectivity can be improved, but its measurement is limited to 45 dB due to the dynamic-range limitation of the measurement system. For higher selectivity values, we have to measure the on-off SBS gain using an optical spectrum analyzer.

The signal degradation brought by the MPF is evaluated using a coherent detection platform as shown in Fig. 9. The AWG with two channels is used to generate both frequency-sweeping signal for SBS pump and OFDM probe signal. A polarization scrambler (PS) after the transmitter is used to demonstrate the polarization-independent characteristic of the filter. After the SBS filter, the OFDM signal is detected using a coherent receiver. The ASE source and the attenuator (ATT) are used to adjust the optical signal to noise ratio (OSNR) of the detected signal for bit rate error (BER) measurement. Offline processing is used to calculate the BER of the signal. We adopt the polarization-independent SBS-based rectangular filter with 2.1 GHz bandwidth to amplify ~4 Gbit/s OFDM signal with QPSK format. For a more precise description of OFDM signal generation and detection, see reference [18].

To achieve the best signal performance with the highest SBS gain and therefore, the highest filter selectivity, we first optimize the pump power and the losses between stages, and achieve the optimal values of 28 dBm and 8 dB respectively. We then tune the input power and measure the SBS on-off gain shown in Fig. 10(a). For a −7 dBm input power, we can achieve a 57 dB cascaded on-off gain, corresponding to a filter selectivity of 57 dB. The insets of Fig. 10(a) show the corresponding gain measurement and QPSK constellations. Even if QPSK constellations are very noisy for low and high input power due to SBS-ASE noise and gain saturation, no error floor has been stated in the −9 dBm to 0 dBm input power range.

In the following measurement, we fix the input power at −7 dBm. Fig. 10(b) shows the BER evolution with SNR for the same gain of 25 dB with different stage-numbers. The four-stage configuration achieves the best performance, which is very close to the back-to-back (BtB) case, proving that multi-stage configuration can improve the signal performance. Fig. 10(c) shows the BER-SNR evolution for the four-stage filter with different gains. The SNR penalty with respect to BtB is only 2.6 dB at a BER of 10^{-3} for a SBS gain of 57 dB.

V. Conclusion

In this paper, we have demonstrated a high selectivity rectangular MPF based on SBS effect in optical fiber. By using a pump-sweeping scheme combined with feedback compensation and pump-splitting dual-stage configuration, a rectangular filter with a selectivity as high as 45 dB has been achieved. The tuning of bandwidth, central frequency and selectivity shows the significant capability of the proposed SBS-based MPF. By using a depolarized frequency-sweeping pump in a pump-splitting four-stage configuration, a polarization-independent rectangular SBS filter with 2.1 GHz bandwidth and 57 dB selectivity has been achieved. The multi-stage configuration can mitigate SBS-ASE; thus, the SNR penalty of 4 Gb/s QPSK-OFDM signal is only 2.6 dB with respect to the BtB case at a BER of 1e-3. So, the proposed SBS filter is very close to meeting all the technical requirements of the desired MPF mentioned in the introduction.

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