

Bandwidth-tunable narrowband rectangular optical filter based on stimulated Brillouin scattering in optical fiber

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Abstract: We propose a rectangular optical filter based on stimulated Brillouin scattering (SBS) in optical fiber with bandwidth tuning from 50 MHz to 4 GHz at less than 15-MHz resolution. The rectangular shape of the filter is precisely achieved utilizing digital feedback control of the comb-like pump spectral lines. The passband ripple is suppressed to ~1 dB by mitigating the nonlinearity influences of the comb-like pump lines generated in electrical and optical components and fibers. Moreover a fiber with a single Brillouin peak is employed to further reduce the in-band ripple and the out-of-band SBS gain at the same time. Finally, we analyze the noise performance of the filter at different bandwidth cases and demonstrate the system performance of the proposed filter with 2.1-GHz bandwidth and 19-dB gain by amplifying a 2-GHz orthogonal frequency-division-multiplexing (OFDM) signal with quadrature-phase-shift-keying (QPSK) and 16-quadrature-amplitude-modulation (16-QAM) on each subscriber.

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1. Introduction

Optical narrowband filtering ranging from MHz to several GHz plays an important role in high-resolution optical signal processing, especially in the context of flexible switching in high speed optical transmission systems [1] and band-pass filtering in microwave photonics [2]. An ideal tunable passband filter has a rectangular response consisting of an ultra-flat passband and very steep edges which bring about many benefits. The flat passband will not distort the signal at all thus keeping high signal fidelity. The steep edges can suppress crosstalk from adjacent bands at the extreme. The wavelength and bandwidth tunability makes it reconfigurable and more flexible to meet different requirements.

Such kind of rectangular filters with large bandwidth have already been achieved by using liquid-crystal on silicon (LCOS) technique [3] and tunable bulk-grating optical filter [4]. However, for both techniques, the flat-top passband shape can only be obtained for bandwidth larger than ~10 GHz. For smaller bandwidth, the filter passband tends to a Gaussian shape, which cannot completely meet ultra-narrow sub-wavelength switching requirements, such as in multi-band orthogonal-frequency-division-multiplexing (MB-OFDM) systems [4]. Several methods have been proposed to implement optical filters with bandwidth in GHz-range: specially designed fiber Bragg gratings (FBG) [5], microring-based optical combs [6], Fabry–Perot etalons [7], forward stimulated interpolarization scattering [8] and Stimulated Brillouin scattering (SBS) [9–13], etc. Among all the above methods, SBS based active filter has been considered as one of the most promising techniques. The wavelength of the SBS-based filter can be tuned easily by tuning the wavelength of the pump. The filter bandwidth and the shape can be also flexibly changed by controlling the pump spectrum using external modulation [9, 10], direct current modulation [11, 12] and cascaded phase and intensity modulation [13]. In addition, the filter extinction ratio can be further increased by the polarization characteristics of the SBS amplification [10, 12]. However, it is very difficult to control the pump spectrum

precisely in the previous works, therefore the exact flat top and sharp edges as the ideal rectangular filter can be hardly achieved.

In this paper, we present a narrowband rectangular SBS filter with tunable bandwidth from 50 MHz to 4 GHz at less than 15-MHz tuning resolution. We modulate the pump using external intensity modulation by an electrical frequency comb whose amplitude and initial phase can be digitally controlled accurately. A feedback compensation process is proposed to control the pump shape precisely. Some preliminary results have been presented previously [14] which shows the validity of the feedback method. On the foundation of the feedback process, we further propose to mitigate the nonlinear effects of the comb-like pump generated in electro-optical components and fiber. Meanwhile we utilize a more suitable fiber with a single significant Brillouin gain peak to improve the filter flatness. As a result, the in-band ripple is decreased to ~1 dB for all bandwidth cases while the unwanted out-of-band gain is further suppressed. Finally, we demonstrate the system performance of the proposed filter by amplifying an OFDM signal with quadrature-phase-shift-keying (QPSK) and 16-quadrature-amplitude-modulation (16-QAM) formats on each sub-carrier, which proves the validity of the SBS based rectangular filter.

2. Rectangular filter shape achieved by feedback control

The natural SBS gain is Lorentzian shape with bandwidth ranging from 10 MHz ~50 MHz depending on different types of fibers [15]. Theoretically, in order to obtain the ideal rectangular SBS gain spectrum, a pump consisting of equal-amplitude spectral lines with interval equaling the natural SBS gain bandwidth is required. Instead of controlling the pump spectrum from the time domain, we firstly generate an electrical frequency comb with equal amplitude at each spectral line using an arbitrary waveform generator (AWG). Then we modulate it with optical carrier-suppression single-sideband (OCS-SSB) modulation to generate an optical frequency comb as the Brillouin pump. The SBS filter bandwidth adjustment is achieved simply by controlling the number of electrical spectral lines so as to the pump spectral lines. In addition, we can control the amplitude, the initial phase of each electrical spectral line and the frequency spacing of spectral lines digitally and precisely. It guarantees that there is no spectral components out of the comb region at all, resulting in a steep-edged pump light, thus the SBS gain spectrum obtained has very steep edges as well, which is unachievable in the previous schemes.

However, given the nonlinear responses of electrical and optical components such as the optical modulator and its driver, the flat electrical spectral lines lead to uneven SBS gain as sketched in Fig. 1. Since the SBS gain exponentially increases with the pump power, even small pump power variation results in great gain difference. Thus an accurate control of each pump line with an effective revision is desired.

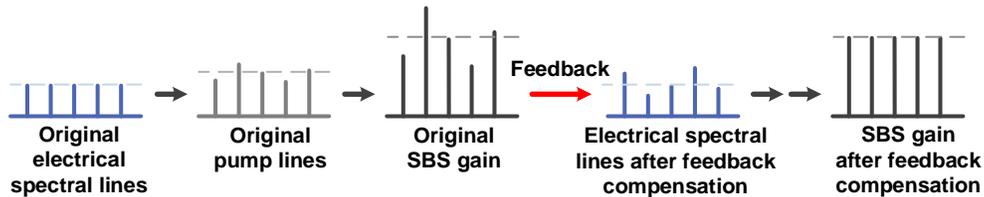


Fig. 1. The electrical spectral lines, pump lines and SBS gains before and after feedback.

The relation between the pump and the SBS gain in classical theory [16] is described in formula (1):

$$\frac{P_s(0)}{P_s(L)} = \exp\left(\frac{g_B P_0 L_{eff}}{A_{eff}} - \alpha L\right) \quad (1)$$

where $P_s(0)/P_s(L)$ is the signal gain, P_0 is the pump power and αL is the fiber loss. When we use logarithmic unit and neglect the fiber loss, the signal gain and the pump power have a linear relation as shown in formula (2):

$$\text{Gain(dB)} \propto P_0 \propto (\text{Pump_amplitude})^2 \quad (2)$$

In our experiment, the electrical signal is from the AWG with the V_{pp} of less than 1V which is much smaller than the V_{pi} of the IQ modulator. So it is reasonable to treat it as small-signal modulation where the electrical and optical signal have an approximate linear relation. Based on this approximation, we can derive the revision Eq. (3) and calculate the new amplitude of each electrical spectral line.

$$\frac{\text{Gain_ideal(dB)}}{\text{Gain_measured(dB)}} = \frac{\text{Pump_amplitude_new}^2}{\text{Pump_amplitude_old}^2} = \frac{\text{Electrical_amplitude_new}^2}{\text{Electrical_amplitude_old}^2} \quad (3)$$

Considering that the SBS gain is only related to the pump power, we just control the amplitude of each electrical spectral line and set a random phase for each line to maintain a good peak to average ratio of the waveform from the AWG.

Based on Eq. (3), we propose an effective feedback compensation scheme as shown in Fig. 2. The general procedure is as follows: Firstly generate the original pump lines by OCS-SSB modulation using flat electrical spectral lines. Then measure the SBS gain spectrum by an electrical vector network analyzer (EVNA) and use Eq. (3) to calculate the new amplitude of every electrical spectral line. Taking into account the linear approximation error and the non-ideal responses of electrical and optical components, a rectangular gain spectrum can only be obtained by repeating the generation, measurement and feedback process successively for several times. Once the feedback compensation is completed, the electrical spectral lines can be recorded for rectangular SBS filter generation.

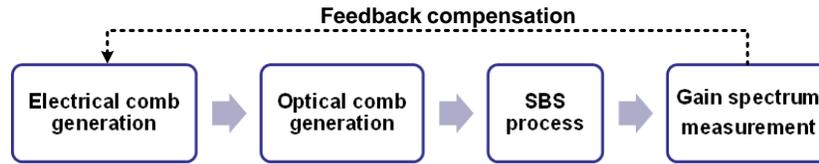


Fig. 2. The feedback compensation method.

The experimental setup is shown in Fig. 3. An external cavity laser (ECL) operating at 1550 nm is split into two branches. In the upper branch, an AWG is used to generate the electrical spectral lines with frequency interval equaling the natural SBS bandwidth of 15 MHz. Then it is modulated on the light to generate the SBS pump lines utilizing an I&Q modulator (IQM). With proper I&Q phase adjustment and bias control of the modulator, the OCS-SSB modulation can be achieved. The OCS-SSB signal is then amplified by an erbium doped fiber amplifier (EDFA) and launched into the 12.5-km single-mode fiber through an optical circulator. The SBS gain is ~11-GHz away from the pump as shown in Fig. 3(i). In the lower branch, a sweeping signal covering the whole SBS gain region from an EVNA is modulated on the light to generate the probe signal. An optical bandpass filter (BPF) removes the left sideband of the probe signal for stable SBS gain measurement as shown in Fig. 3(ii). Then the probe light goes through the fiber and is amplified once it sweeps within the SBS gain region as shown in Fig. 3(iii). A polarization controller (PC3) is used to achieve the maximum SBS gain. After the SBS process, the probe signal is detected by a photodiode (PD) and then sent into the EVNA. The amplitude and phase responses are measured by the EVNA and the SBS gain spectrum can be obtained by subtracting the results with and without the SBS amplification.

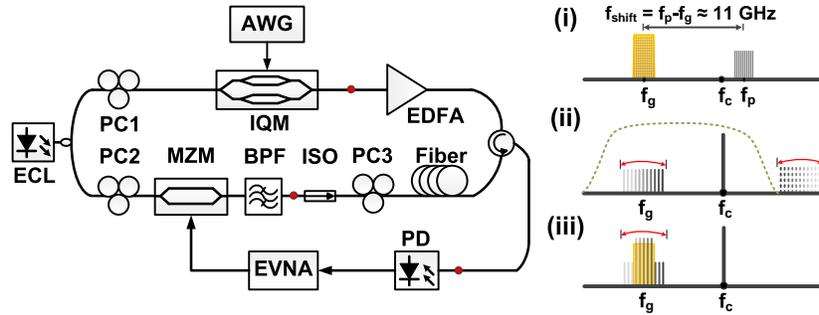


Fig. 3. Experimental setup. Inset (i) single sideband pump f_p , SBS gain around f_g , and ECL laser frequency f_c , (ii) sweeping probe signal, (c) sweeping probe signal amplified by the SBS gain.

The measured SBS gain spectra with 500-MHz bandwidth are shown in Fig. 4. Figures 4(a) and 4(b) are the SBS gain spectrum and phase response before implementing the feedback compensation. Figure 4(c) shows the flat electrical spectral lines generated by the AWG. Due to the non-ideal frequency response of the I&Q modulator and its electrical driver, the pump spectral lines become uneven and the corresponding SBS gain ripple is as high as 5 dB accompanying remarkable unwanted out-of-band gain. Meanwhile the curve of the phase response is quite rough due to the large amplitude ripple. After implementing the feedback process for several times, we obtain the SBS gain spectrum shown in Fig. 4(e). The gain is about 25 dB and the maximum ripple is reduced to 0.7 dB. In the meantime the curve of the phase response is very smooth as shown in Fig. 4(f). The 3-dB and 15-dB bandwidths are 493 MHz and 539 MHz respectively, corresponding to a shape factor (SF_{15dB}) of 1.093, which is close to the ideal rectangular case of 1. Here, the SF_{15dB} is defined as the ratio of filter bandwidth at 15 dB to 3 dB to characterize the steepness of the filter edge. The corresponding electrical spectral lines are shown in Fig. 4(d), which are totally different from the original in Fig. 4(c) and unpredictable, thus proving the importance and validity of the feedback compensation method.

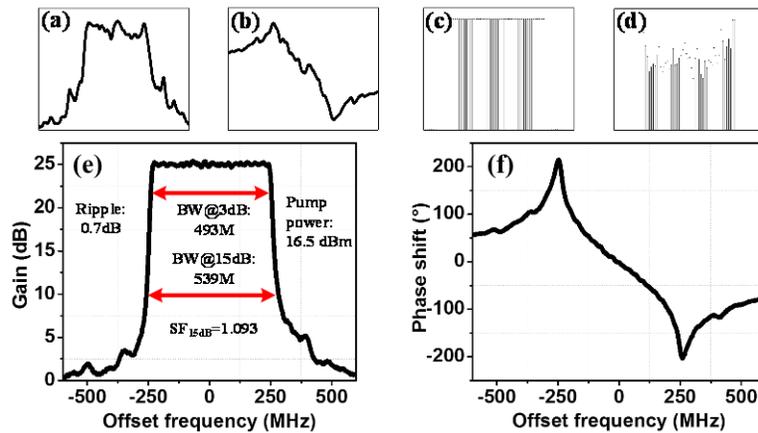


Fig. 4. (a) The original SBS gain spectrum, (b) the phase response and (c) corresponding electrical spectral lines. (e) The SBS gain spectrum, (f) phase response and (d) corresponding electrical spectral lines after feedback process.

3. Bandwidth increase and flatness improvement

In the feedback process it is assumed that the SBS gain at a certain frequency is only related to the corresponding electrical spectral line. It works well when the filter bandwidth is small.

However, with the increase of the filter bandwidth, the increasing pump power and number of spectral lines cause remarkable four-wave mixing (FWM) in the optical fiber which redistributes the pump power and generates new spectral lines at the stop band. Another factor not taking into account is the nonlinearity of the modulation such as third-order intermodulation that also introduces new spectral lines and cannot be neglected when the pump power is large. The nonlinearity induced spectral components are sketched in Figs. 5(a) and 5(b) in the color of yellow. It results in a partial failure of the feedback process leading to larger passband ripple and out-of-band gain. Therefore an effective nonlinearity management is required.

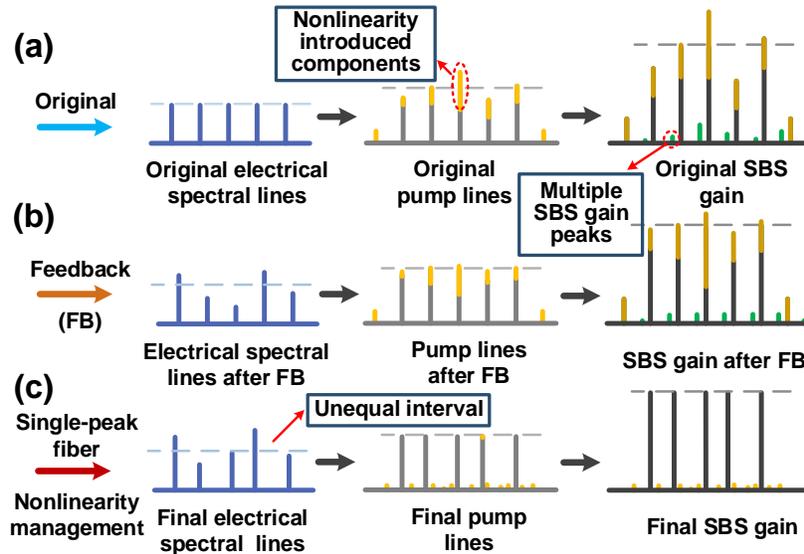


Fig. 5. The electrical spectral lines, pump lines and the SBS gains in different cases.

We propose a nonlinearity management method as shown in Fig. 5(c). We set frequency interval of the electrical spectral lines randomly around the natural SBS gain bandwidth instead of the equal interval, i.e. 14 MHz, 15 MHz and 16 MHz. In this case the new spectral lines generated by the FWM and the nonlinear modulation are no longer superposing on the original lines. As a result, the power of these new spectral lines is very small compared with the original lines and can just induce tiny gain or even under the threshold of SBS effect. Therefore the flatness of the passband gain can be greatly improved and the unwanted out-of-band gain can be partly suppressed as well.

In Fig. 6 we demonstrate the comparison of the SBS gains between the equal intervals and unequal intervals. We set four electrical spectral lines and measure the SBS gains in different conditions. To clearly observe the amplitude variation of each SBS peak, the equal intervals are all set to 200 MHz while the unequal intervals are set to 199, 200 and 201 MHz separately. The total pump power is ~ 10.5 dBm. In the equal interval case, the newly generated frequency components by FWM and modulation nonlinearity superpose with the original pump lines therefore interference happens. The phase relationship among the different pump lines will affect the power of the pump lines due to nonlinearities, resulting in different SBS gain spectra. For the sake of showing the nonlinear effects, we change the initial phase of the first electrical spectral line on the left so as to change the phase relations of the pump lines, the SBS gain variation is clearly observed and the out-of-band SBS gain is as high as 5 dB as shown in Fig. 6(a). For \sim GHz SBS gain with only 15-MHz interval, the number of the pump spectral lines is several hundred. Therefore the condition is much more complicated and it is very difficult to control the phase relationship among the pump lines to

achieve flat SBS gain. However, when the intervals are set unequal, it is hard to distinguish the difference among the different cases and the out-of-band SBS gain is also significantly reduced as shown in Fig. 6(b) since the newly generated frequency components do not superpose with the original pump lines. We call this uneven pump interval method as nonlinearity management.

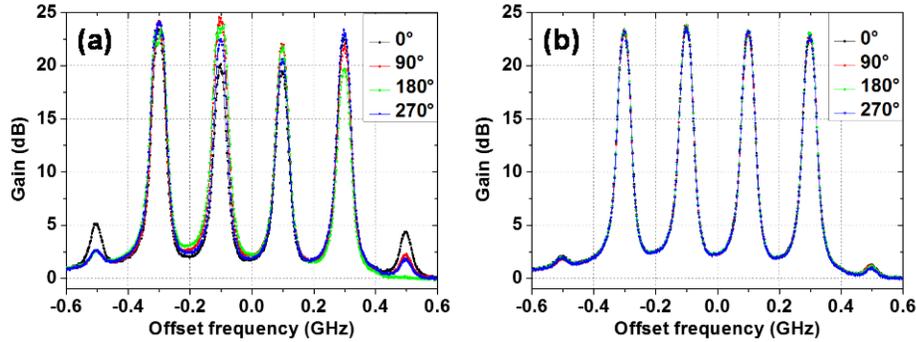


Fig. 6. 4 SBS gain peaks with (a) equal intervals and (b) unequal intervals.

Moreover, the natural SBS gain spectrum is related to the material doping profile [17] and the structure of the fiber [18]. In the Germanium-doped G-652 fiber that we used in the previous work [14], there are 4 SBS peaks (i.e. four first L_{om} acoustic modes) as sketched in Figs. 5(a) and 5(b) in the color of green while the measured result is shown in Fig. 7(a). The multiple minor SBS gain peaks superpose with other main SBS gain peaks generated by different pump lines and will affect the feedback process. It contributes to the un-flat filter passband and induces out-of-band gain as well. Therefore we employ a fiber with a single Brillouin peak (a standard single-mode fiber in our lab) as shown in Fig. 7(b) which is highly desired in our experiment. By employing both the nonlinear management and the new fiber with single Brillouin peak, the final SBS gain will be ultra-flat as sketched in Fig. 5(c).

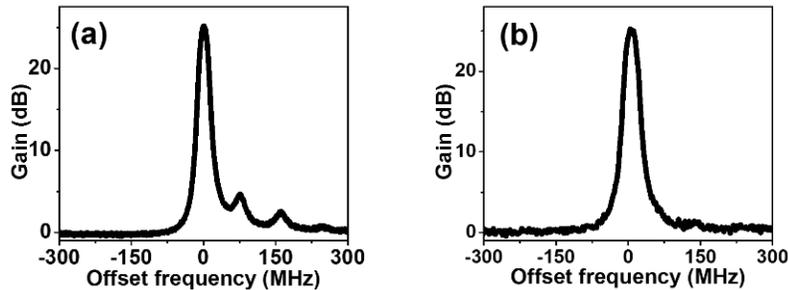


Fig. 7. The natural SBS gain in (a) G-652 fiber (b) fiber with a single Brillouin peak.

The measured SBS spectra with 3-GHz bandwidth in different cases are shown in Fig. 8. The original SBS gain generated by the electrical spectral lines with equal amplitude and equal frequency interval are seriously affected by the non-flat frequency response and nonlinearities of the electrical and optical components. As shown in Fig. 8(a), the SBS gain is far from the rectangular shape. When implementing the feedback compensation as shown in Fig. 8(b), the ripple is still as high as 3.70 dB with large unwanted out-of-band gain. After utilizing the unequal interval spectral lines, the passband ripple in Fig. 8(c) is significantly reduced to 1.56 dB. By further employing the single-peak fiber, the ripple is further decreased to 1.00 dB shown in Fig. 8(d) and the out-of-band SBS gain is also smaller than the previous cases. In the meantime, the number of feedback iterations decreases from dozens of times to ~10 times. We can further decrease the in-band ripple by implementing more feedback

iterations, but ~ 1 dB ripple already satisfies most of the applications. Besides, the ripple measurement accuracy is also limited by the power measurement precision of the EVNA.

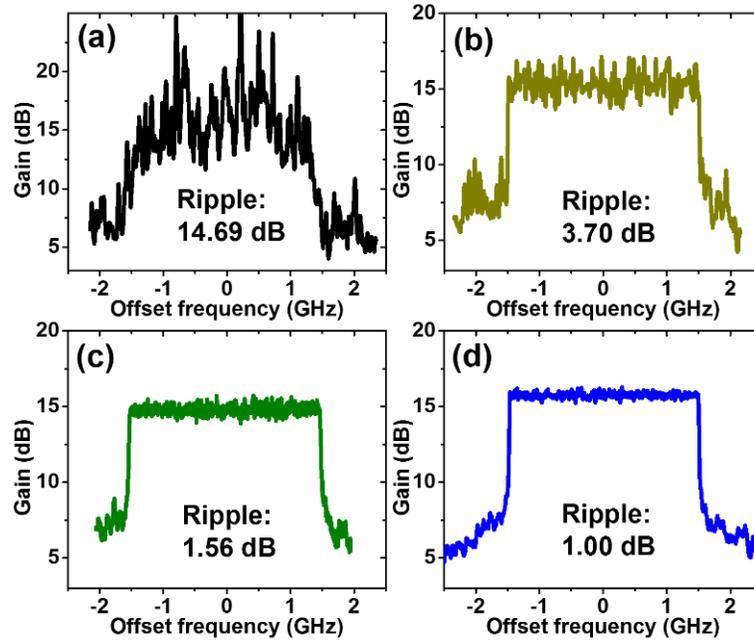


Fig. 8. The measured SBS spectra (a) original spectrum (b) after feedback process (c) utilizing nonlinearity management (d) utilizing nonlinearity management with single-peak fiber.

Meanwhile, the nonlinearity management (i.e. random interval between the electrical spectral lines) also improves the shape factor of the filter. The 1-GHz SBS filter without and with nonlinearity management are shown in Figs. 9(a) and 9(b) respectively. After implementing the nonlinearity management, the shape factor is further reduced from 1.167 to 1.075 which is almost the ideal rectangular case.

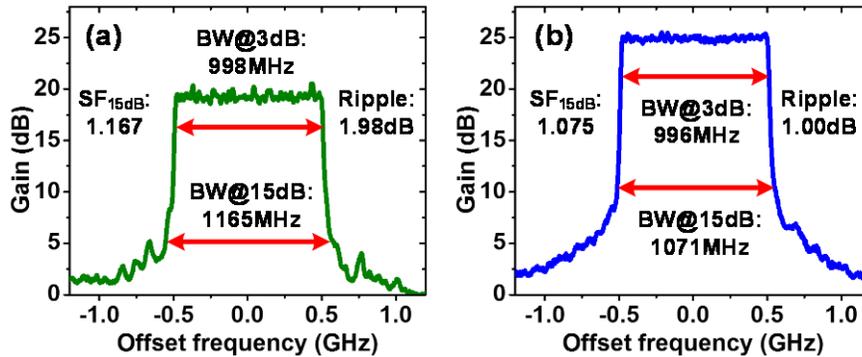


Fig. 9. The 1-GHz SBS filter (a) after feedback process (b) utilizing nonlinearity management with single-peak fiber.

The bandwidth of the proposed filter can be changed flexibly with a resolution of around 15 MHz by changing the number of the electrical spectral lines generated by the AWG. The bandwidth tuning resolution can be less than 15 MHz if we reduce the frequency spacing between the first and the second pump lines with a step less than 1 MHz, which is achievable by digital means. The gain spectra and phase responses of different filter bandwidths ranging from 50 MHz to 4 GHz are shown in Figs. 10(a) and 10(b) respectively. The SBS gain values

and the corresponding pump power levels are shown in Fig. 10(c). Note that in the experiment, we use two cascaded EDFAs to amplify the original weak pump. The needed pump power is dependent on the power of the original pump and the optical filter bandwidth between the two EDFAs. In Fig. 11 the passband ripple and filter gain are compared among 3 conditions: only using feedback compensation (FB), using both FB and nonlinearity management (NM), using FB and NM in the single-peak fiber (SPF). The figures illustrate that in the third case the SBS filter has the largest gain and smallest ripple thus proving the validity of the NM in the SPF.

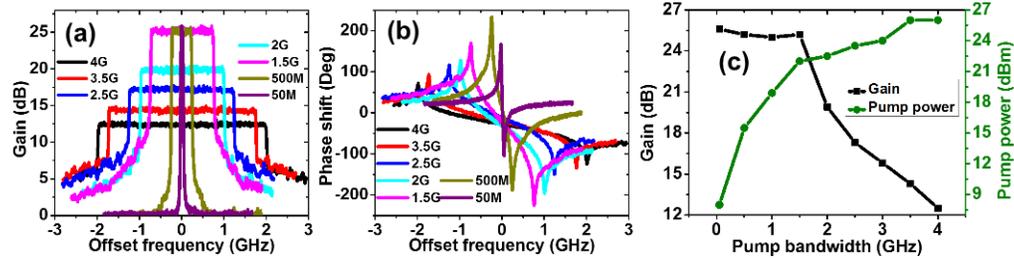


Fig. 10. The (a) gain spectra and (b) phase responses of SBS filters with different bandwidths. (c) The corresponding pump power with different bandwidth.

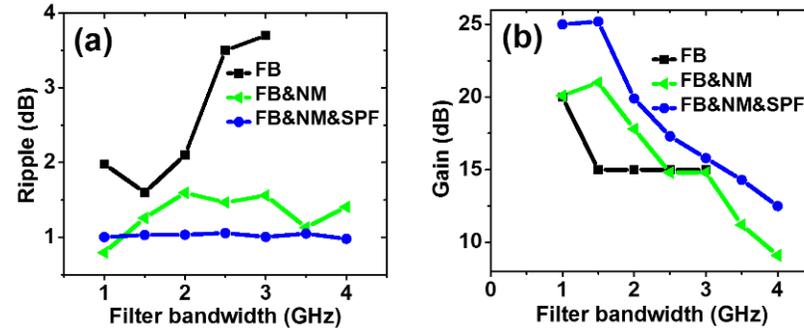


Fig. 11. The (a) passband ripple and (b) filter gain comparison among 3 conditions: only using feedback compensation (FB), using both FB and nonlinearity management (NM), using FB and NM in the single-peak fiber (SPF).

Limited by the experimental equipment and proposed method, the extinction ratio of large bandwidth filter is small. The SBS gain limitation and the unwanted out-of-band SBS gain are the two main issues. As shown in Fig. 11(b) the SBS gain is decreased with the increase of the filter bandwidth. When the pump power is higher than several hundreds of mW [16], it starts acting as the Raman pump at the same time which will consume the SBS pump power. Therefore the SBS gain at large bandwidth cannot be effectively increased by simply increasing the pump power. A potential solution is using special fiber with high SBS gain efficiency such as Chalcogenide fiber [19]. The high gain at large SBS bandwidth can be achieved with smaller pump power. It will also mitigate the FWM effect and reduce out-of-band gain to some extent. The filter extinction ratio can be further increased not only by increasing the SBS gain but also by the polarization characteristics of the SBS amplification [12]. Since the state of polarization (SOP) of the SBS amplified signal is governed by the SOP of the pump, it is easy to distinguish the in-band amplified signal from the out-of-band unamplified signal or noise just by using a polarizer before the receiver and controlling the pump SOP carefully.

Another critical issue is the out-of-band gain which not only degrades the extinction ratio of the filter but also induces in-band crosstalk if the filtered signal will be combined with another signal. The crosstalk induced penalty is dependent on the modulation format [20, 21],

the original signal power [22] and also the frequency spacing from the filtered signal. If we take QPSK signal as an example where 16-dB crosstalk induces 1-dB penalty and assume that the added signal is 1-GHz away from the SBS amplified signal with the same power level, the maximum available filter bandwidth is ~ 2 GHz.

4. Filter performance analysis and evaluation

It is well-known that the Brillouin amplification is accompanied with strong noise [23]. We analyze the noise performance of the proposed SBS filter by amplifying a signal with 200-MHz single-frequency modulation and measure the signal to noise ratio (SNR). Figure 12(a) shows the spectrum of the SBS amplified signal. The spectrum is calculated from the waveform obtained by an oscilloscope with coherent detection since we do not have a high-resolution optical spectrum analyzer (OSA). The proposed filter is 1.5 GHz wide with 20 dB gain and ~ 1 dB passband ripple. The symmetric frequency is due to the carrier-suppressed double-sideband modulation by the Mach-Zehnder modulator. We do not use the CW light as the signal since the DC noises from the oscilloscope is significant. The optical power of the single-frequency signal is fixed at ~ 30 dBm. Figure 12(b) illustrates the SNR variation trend with the increase of the filter bandwidth. Here we use the signal peak power and the average in-band noise power to calculate the SNR. The corresponding pump power is redraw here for information. Note that the SBS gain is decreased with the increase of the pump bandwidth. We define the SNR penalty at 0.5-GHz bandwidth as 0 dB since the SNR penalty is not obvious at small bandwidth case. As shown in the figure, the relative SNR penalty from the SBS filter is increased with the increase of the filter bandwidth, which can be explained as the reduced pump efficiency at large bandwidth case. When the bandwidth reaches 4 GHz, the relative SNR penalty is ~ 11.7 dB. Figure 12(c) demonstrates the SNR variation with different pump power but the same bandwidth of 2 GHz. The SNR penalty starts to increase when the pump power exceeds ~ 20 dBm. To sum up, the filter performance will be degraded gradually when the pump power is high or the filter bandwidth is large. The practical applications should compromise between high gain and large bandwidth.

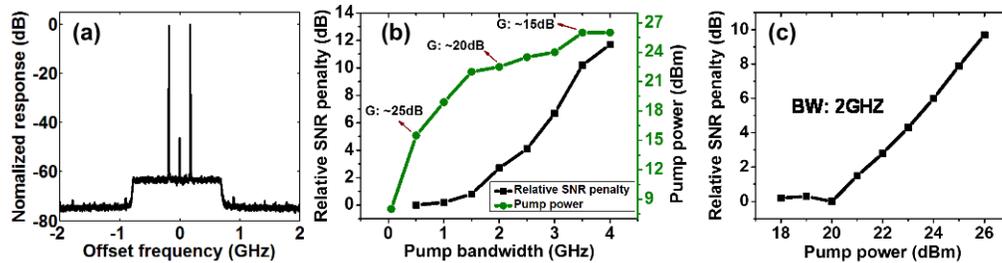


Fig. 12. (a) Electrical spectrum of the SBS amplified signal with single-frequency modulation. (b) The relative SNR penalty with different pump bandwidth. (c) The relative SNR penalty with different pump power but the same bandwidth of 2 GHz.

To further validate the feasibility of the SBS based filter, we use the designed rectangular SBS filter to amplify the OFDM signal and then measure the system performance. We firstly generate a 2-GHz single polarization OFDM signal with QPSK and 16-QAM modulation format for each subcarrier. The OFDM signal is generated using an AWG with the sampling rate of 2.5-G Samples/s, corresponding to 2.4-Gb/s and 4.8-Gb/s net bit rate respectively with overhead for channel estimation, phase noise and dispersion compensations. 128 subcarriers are used taking into account the ~ 100 -KHz ECL laser linewidth. For a more precise description of OFDM signal generation and detection, see references [4, 24]. Then we use an SBS rectangular filter with 2.1-GHz bandwidth and 19-dB gain to amplify the OFDM signal and evaluate the SBS filter performance. The power of the OFDM signal launched into 25-km fiber is around -10 dBm. The amplified OFDM signal is detected by intradyne coherent

receiver followed by high-speed real time oscilloscope and the QPSK and 16-QAM constellations are achieved by off-line processing [24]. The off-line processing also allows us to employ a digital filter with very sharp cut-offs so that the out-of-band SBS gain will not induce any penalty. Figures 13(a) and 13(b) show the QPSK constellations without and with the SBS filter respectively, while Fig. 13(c) shows the corresponding error vector magnitudes (EVMs) for each data subcarrier. For fair comparison, the received power at the coherent receiver is tuned at -12 dBm for both cases, corresponding to the optimal received power of the coherent receiver therefore the performance degradation is only from the SBS amplification noise. Figure 14 show the 16-QAM constellations and the corresponding EVMs without and with the SBS gain filter. The EVM penalty is only ~ 0.04 for both QPSK and 16-QAM cases, which proves the SBS gain induced penalty is not significantly, validating the feasibility and usefulness of the proposed rectangular SBS gain filter.

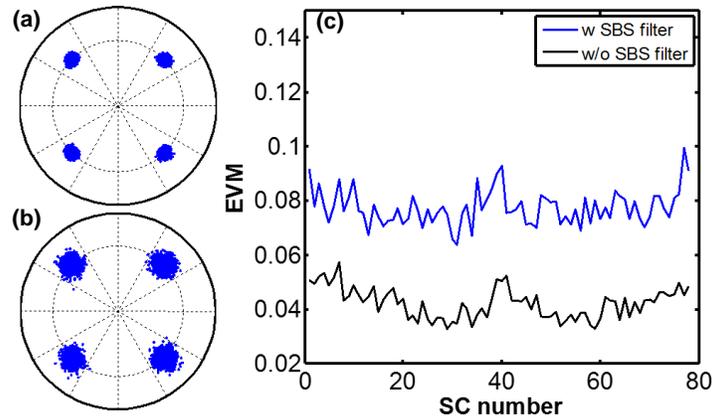


Fig. 13. The QPSK constellations (a) without and (b) with the SBS filter, (c) corresponding EVMs in two cases.

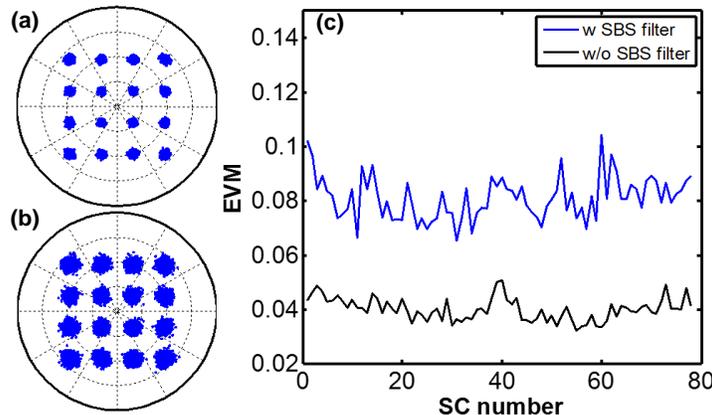


Fig. 14. 16-QAM constellations (a) without and (b) with the SBS filter, (c) corresponding EVMs in two cases.

5. Conclusions

We have presented an ultra-flat rectangular optical filter based on stimulated Brillouin scattering and demonstrated a typical application of amplifying an OFDM signal with QPSK and 16-QAM modulation formats. On the foundation of the feedback process, we propose the method of utilizing unequal interval spectral lines to mitigate the nonlinear effects in electro-optical components and fiber, meanwhile employing a fiber with only a single Brillouin gain

peak. As a result, the in-band gain ripple is further reduced to as low as ~1 dB. With flexible bandwidth from 50 MHz to 4 GHz and high tuning resolution of less than 15 MHz, the proposed steep-edged rectangular filter can find versatile applications in optical and microwave signal processing.

Acknowledgments

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