High Resolution Programmable Optical Filter Based on Stimulated Brillouin Scattering: Design and Applications

(Invited)

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***Abstract*—We propose a versatile optical filter with precisely reconfigurable shape based on stimulated Brillouin scattering effect in optical fiber using digital feedback compensation. Filter application for optical sub-band separation-aggregation of multi-band OFDM signal is demonstrated.**

I. INTRODUCTION

Optical narrowband filtering ranging from MHz to several GHz plays an important role in high-resolution optical signal processing, such as in flexible switching of high speed optical transmission systems [1] and bandpass filtering in microwave photonics [2]. An ideal passband filter should have an ideal rectangular response (i.e. an ultra-flat top and very steep edges), which can keep high signal fidelity and suppress out-of-band noise at the extreme. Moreover, in order to meet different requirements, the filter wavelength and bandwidth tunability is also highly desired. Such kind of rectangular filters with large bandwidth have already been achieved by using bulk-grating technique [3], liquid-crystal on silicon (LCOS) [4] and arrayed-waveguide grating [5]. For implementing GHz-bandwidth filter, several solutions have been proposed including specially designed fiber Bragg gratings (FBG) [6], cascaded micro-ring resonators [7] and stimulated Brillouin scattering (SBS) [8], etc. Among all the above methods, SBS based active filter has been considered as one of the most promising techniques with inherent flexibility. However, it is very difficult to control the pump spectrum precisely in the previous works. Therefore an ideal rectangular filter with the exact flat top and sharp edges is always a daunting challenge.

In this paper, we demonstrate a programmable narrowband rectangular optical filter based on SBS effect with high spectral resolution. By controlling the pump spectrum precisely with digital feedback compensation and nonlinearity management in a single Brillouin gain peak fiber, a steep-edged flat-top filter has been achieved with ~1-dB passband ripple [9]. The filter bandwidth can be precisely tuned from 100 MHz to 3 GHz with resolution of less than 15 MHz. The filter selectivity can reach more than 30 dB by using pump-splitting dual-stage scheme [10]. This filter generation method also has the potential ability to realize arbitrary filter shape. Based on the rectangular filter, we realize a novel reconfigurable optical add and drop multiplexer (ROADM) structure and demonstrate multi-band OFDM signal separation-aggregation in QPSK and 16-QAM formats [11]. The system performance shows that only small penalties are induced by filtering and proves the feasibility of the proposed filter.

II. PROOGRAMMABLE FILTER GENERATION

The most critical factor of the filter design is to control the Brillouin pump precisely so as to control the filter shape. To achieve this, we first use an arbitrary waveform generator (AWG) to generate an electrical comb. Then the electrical comb modulates a CW light to generate the optical comb acting as the pump. The programmable AWG allows us to control the amplitude and the initial phase of each spectral line in the electrical comb digitally and precisely. Thus the pump spectrum can also be accurately adjusted and lead to a desired filter shape. Note that the filter can be either bandpass with SBS amplification or band-stop with SBS absorption. As shown in Fig. 1, in order to obtain a rectangular gain spectrum using Lorentzian-shape natural SBS gain, a pump consisting of equal-amplitude spectral lines with the frequency space of the natural SBS gain bandwidth is required. In the rest of this section, we only discuss the rectangular passband filter as a typical example, but theoretically the filter shape can be arbitrarily designed.

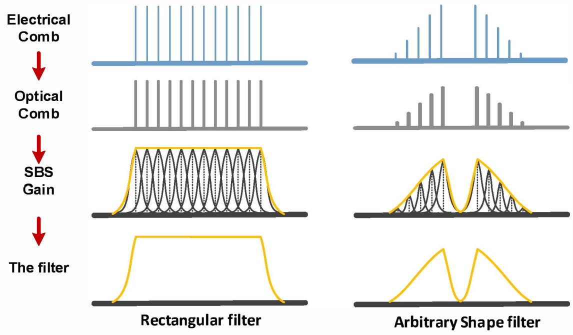

Fig. 1. The principle of the filter generation

Given the nonlinear responses of electrical and optical components, the flat electrical spectral lines actually lead to uneven SBS gain as shown in Fig. 2(a), thus a feedback

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compensation is proposed to digitally control the amplitude of each electrical spectral line according to the measured SBS gain so as to optimize the shape of the targeted SBS filter as shown in Fig. 2(b). In order to mitigate the incalculable gain induced by four wave mixing (FWM) effect among the multiple pump lines as shown in Fig. 2 with yellow color, we set frequency interval of the electrical spectral lines randomly around the natural SBS gain bandwidth instead of the equal interval. In this case the FWM induced gain is no longer superposing on the original lines and the feedback process is more accurate.

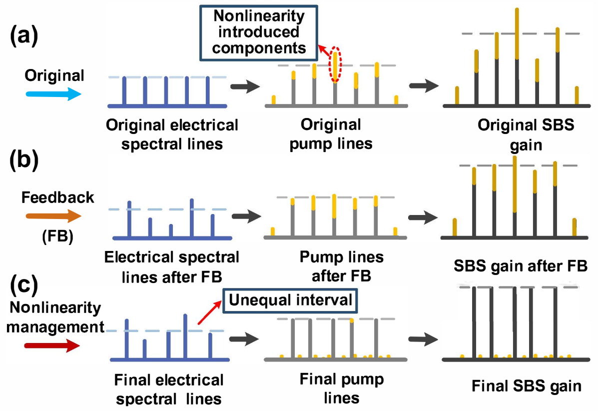

Fig. 2. The feedback compensation and nonlinearity management for improving the filter passband flatness.

In order to increase the filter selectivity, we propose a pump-splitting dual-stage scheme. Instead of using a single pump with high power, we split it into two stages and amplify the signal twice successively. In this case, the pump power of each stage is not too high to stimulate high Raman gain nor to induce too much out-of-band FWM components [10]. Thus the filter selectivity can be increased dramatically.

The experimental setup is shown in Fig. 3. A distributed feedback (DFB) laser is split into two branches for the generation of pump and probe signal. In the upper branch, the electrical spectral lines from the AWG modulates the CW light to generate the optical carrier-suppressed single-sideband (OCS-SSB) SBS pump lines utilizing an I&Q modulator (IQM). After being boosted by a high power erbium-doped fiber amplifier (EDFA), the OCS-SSB signal is then split into two parts equally and send into two identical 25-km long SMFs. In the lower branch, a sweeping signal covering the whole SBS gain region from an electrical vector network analyzer (EVNA) modulates the CW light to generate the probe signal. After suppression of the left sideband by an optical bandpass filter (BPF), the probe light propagates in the two fibers successively and is amplified once it has swept within the SBS gain region. An optical attenuator (ATT) between the two stages can prevent signal saturation in the second stage therefore effectively increase the filter selectivity. The probe signal is then detected by a photodiode (PD) and sent into the EVNA. The amplitude and phase response is measured by the EVNA and the SBS gain spectrum can be obtained by comparing the results between the SBS pump switched on and off.

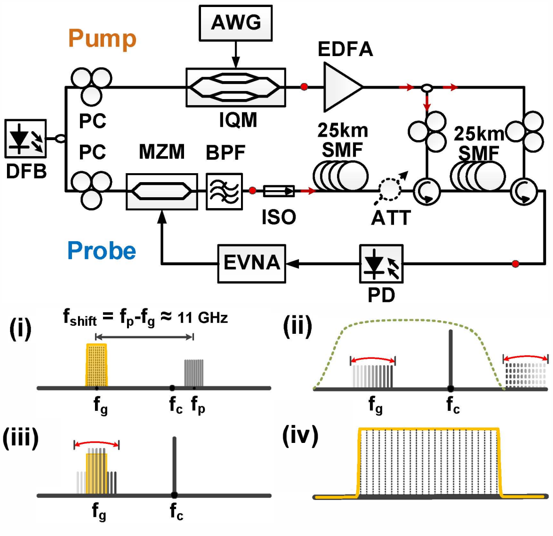

Fig. 3. The experimental setup. Inset (i) DFB laser frequency f_c, single sideband pump f_p and SBS gain around f_g, (ii) sweeping probe signal, (iii) sweeping probe signal amplified by the SBS gain, (iv) measured gain

Only 5-10 iterations of the digital feedback compensation are required to obtain the rectangular filter shape as show in Fig. 4. The filter selectivity can be tuned by changing the total pump power. The filter bandwidth can also be tuned by changing the number of the electrical spectral lines. No matter what the filter selectivity and bandwidth are, the passband ripple can always be controlled within 1 dB and the filter edges are very steep. The out-of-band gain is due to the FWM components which cannot be mitigated completely.

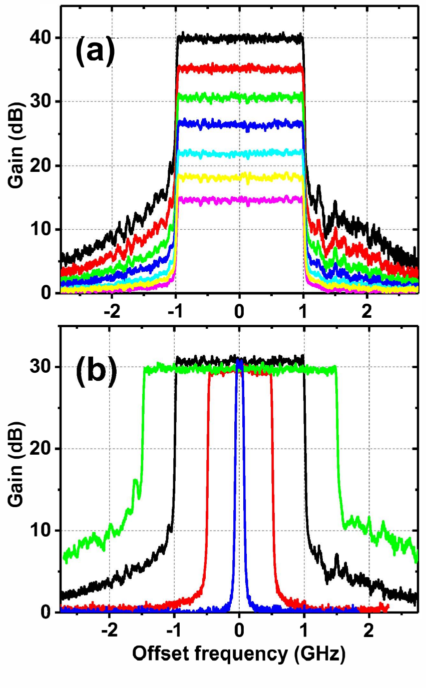

Fig. 4. Rectangular filter with different gains and bandwidths

III. FILTER APPLICATION IN ROADM

The ROADM is an important function in an optical network where optical signals can be added in or dropped from the original signals. Based on the rectangular filter, we have realized a flexible-grid ROADM structure as shown in Fig. 5. An SBS gain filter (bandpass) only keeps the desired sub-band to realize the drop function meanwhile an SBS loss filter

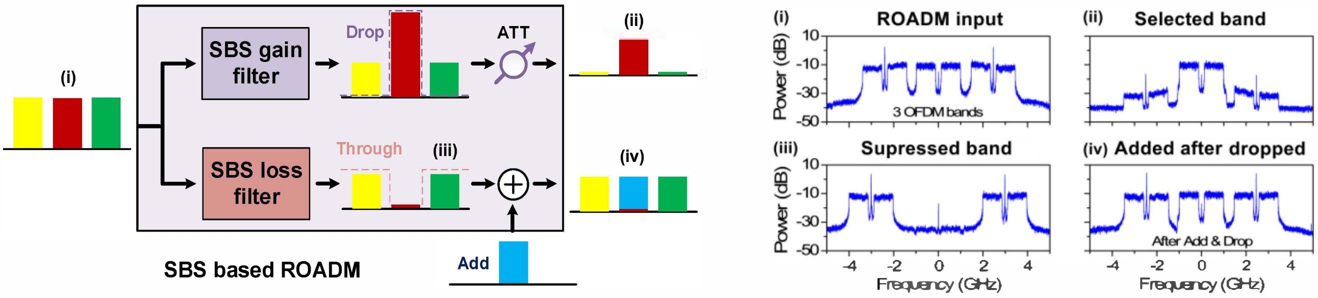

Fig. 5. The concept of the SBS-based ROADM and the measured electrical spectra using a coherent receiver

(band-stop) removes the sub-band in the MB-OFDM signal to empty the spectral band for another sub-band signal to add in. Thanks to the filter central wavelength and bandwidth tunability, the ROADM can be flexibly configured with very high resolution. Meanwhile the guard band between different sub-bands can be set very small benefiting from the rectangular filter shape.

We build the whole transmission system including an ultra-dense WDM signal for the transmitter, an SBS-based ROADM and a coherent receiver for demonstrating the signal separation-aggregation. The WDM multiplexed signal consists of 3 OFDM bands with 2-GHz bandwidth and 1 GHz to 300 MHz band gaps in QPSK or 16-QAM format. In the ROADM, the 3 OFDM bands signal are split into 2 parts, and the central band is amplified or absorbed by a 2.2-GHz rectangular dual-stage SBS gain or loss filter. The extra 200 MHz is dedicated to laser thermal drift mitigation. Then we add the amplified central band of one branch to the empty space of the other branch and send the 3 OFDM bands signal to the receiver. The electrical spectra in Fig. 5 show obvious precise amplification and complete absorption. In order to further prove the filter feasibility, we measure the BER performance of the central sub-band in different conditions. The BER-SNR curves and constellation diagrams are shown in Fig. 6. After being amplified by the SBS gain filter with 25-dB gain as the case in Fig. 5(ii), the SNR penalties are only ~0.5 dB and ~2 dB at a BER of 10^{-3} for QPSK and 16-QAM respectively. When the amplified central sub-band is inserted into the empty central notch, the SNR-BER curves for the QPSK format indicate that there is no obvious penalty induced by the add/drop function even when the guard band is as narrow as 300 MHz. Meanwhile for 16-QAM signal, ~2 dB extra penalty is observed due to residual in-band crosstalk induced by the SBS loss filter.

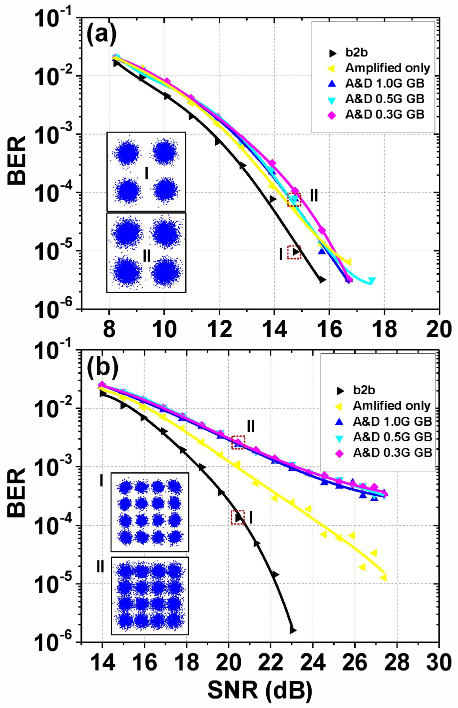

Fig. 6. BER-SNR performance after the add & drop for sub-band OFDM signal with (a) QPSK and (b) 16-QAM formats. A&D represents add and drop and GB represents guard band.

IV. CONCLUSION

We have presented a programmable narrowband optical filter based on SBS effect in a single Brillouin gain peak fiber. As an example, steep-edged flat-top filters with tunable bandwidth from 100 MHz to 3 GHz has been realized with very high control precision which is ensured by the effective digital feedback process. The filter passband ripple is within ~1 dB resulted from the feedback and nonlinearity management. The filter selectivity can reach more than 30 dB by using pump-splitting dual-stage scheme. We have also realized an SBS filter based ROADM structure and demonstrated multi-band OFDM signal separation-aggregation in QPSK and 16-QAM formats. For QPSK format signal, the filter induced penalty is only ~1 dB. With high control precision and high flexibility, the proposed filter will find versatile applications in optical signal processing and microwave photonics.

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