A Bandwidth-Tunable Narrowband Rectangular Optical Filter Based on Stimulated Brillouin Scattering

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Abstract: We present a narrowband rectangular optical filter based on stimulated Brillouin scattering in fiber utilizing digital feedback gain control. The reconfigurable filter with bandwidth from 50 MHz to 3 GHz is demonstrated with 10-MHz resolution.

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1. Introduction

Narrowband rectangular optical filters with bandwidth ranging from MHz to several GHz are highly desired for radio-frequency and microwave photonic signal processing, which can effectively suppress the crosstalk from neighbor frequency bands. Several methods have been proposed to implement such kind of filters, including specially designed fiber Bragg gratings (FBG) [1], forward stimulated interpolarization scattering [2] and Fabry–Perot etalons [3]. In [1] an FBG based filter with 3-dB bandwidth of ~650 MHz and 15-dB bandwidth of ~980 MHz was demonstrated, corresponding to a 15- to 3-dB shape factor (SF15dB) of 1.508, which was claimed as the narrowest rectangular all-fiber optical filter. However, it is still far from the requirement of an ideal rectangular filter with a shape factor of 1. The design of such a rectangular narrowband filter is a great challenge.

On the other hand, stimulated Brillouin scattering (SBS) in optical fiber has been proposed to act as an active optical filter with tunable bandwidth ranging from 10 MHz to several GHz. By controlling the pump spectrum using external phase modulation [4], direct current modulation [5] and cascaded phase and intensity modulation [6], the SBS gain can be broadened and spectral-shaped. The SBS gain with several GHz bandwidth and a flat top has been realized using these techniques [4-6]. But until now, there is no rectangular SBS gain demonstration since the steep edge is the most difficult part due to the gradual change characteristic of the pump spectrum at the edge.

In this paper, we present a narrowband rectangular SBS gain with tunable bandwidth from 50 MHz to 3 GHz with 10-MHz resolution using external intensity modulation by multiple frequency components, and the amplitude of each frequency component can be digitally controlled. A feedback compensation process is proposed to control the pump lines, so as to improve the top flatness and the edge steepness of the gain spectrum. For a 500-MHz SBS gain, the SF15dB is 1.093 and the gain ripple is +/-0.35 dB, which are close to the ideal rectangular filter case.

2. Principle

To achieve an ideal 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. The pump spectral lines can be generated and controlled digitally using arbitrary waveform generator (AWG), so it is easy to suppress the frequency components out of the desired pump spectral region, resulting in a SBS gain spectrum with steep edges. However, due to the non-flat frequency response of the modulator and its driver, equal-amplitude spectral lines will lead to uneven SBS gain as shown in Fig. 1. (a). 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 the pump lines is desired and effective feedback compensation is required.

![Diagram](W4F5.pdf)

Fig. 1. (a) The electrical spectral lines, pump lines and the SBS gains before and after the feedback process. (b) The feedback process.

We propose a simple feedback compensation scheme, as shown in Fig. 1 (b). The general procedure is as follows: Firstly generate the original pump lines by intensity modulation using flat electrical spectral lines. Then measure the SBS gain spectrum by an electrical vector network analyzer (EVNA) and use the formula (1) to calculate the new pump amplitude of every spectral line.
\[
Pump\_new = Pump\_old \times \sqrt{1 - EF} \times \frac{(Gain\_measured - Gain\_ideal)}{Gain\_measured}
\]  \( (1) \)

The EF in the formula is an experience factor which is set according to the specific situation. Repeat the generation, measurement and feedback process successively until a rectangular gain spectrum is obtained. Once the feedback compensation is completed, the electrical spectral lines can be recorded for rectangular SBS filter generation.

3. Experiment and results

The experiment setup is shown in Fig.2 (a). A laser operating at 1550 nm was divided into two parts to generate the Brillouin pump and the probe light. In the upper path, an AWG (Tektronix AW7122C) was used to generate the electrical spectral lines with a fixed frequency spacing, which was then modulated on the light to generate the SBS pump lines utilizing a dual-parallel Mach-Zehnder modulator (DPMZM). The natural SBS bandwidth of the used single mode fiber (SMF) in this experiment was about 10 MHz, thus the electrical frequency spacing of the spectral lines was set at 10 MHz. With 4 channels of electric signals in phase shift of 0, 90, 180, 270 degree from the AWG and proper bias voltages of the DPMZM, the optical carrier suppressed single sideband (OCS-SSB) modulation was achieved. Fig.2 (b) shows the pump spectrum of the modulated OCS-SSB light, where the bandwidth of the signal was set to 1.5 GHz, corresponding to 150 pump lines. The OCS-SSB signal was then amplified by an erbium doped fiber amplifier (EDFA) and launched into a 20-km SMF through an optical circulator for generating the SBS gain. In the lower path, a sweeping signal from an EVNA was modulated and the sweeping range covered the whole SBS gain region. An optical filter (OF) removed the left sideband of the modulated signal for stable SBS gain measurement. Then the probe light went through the SMF and was amplified when the sweeping probe tuning into the SBS gain region. A polarization controller (PC3) was used to get the maximum SBS gain. The output probe signal was detected by a photo-detector (PD) and then sent into the EVNA. The S21 parameters including amplitude and phase characteristics were measured by the EVNA and the SBS gain spectrum can be obtained by subtracting the results with and without the SBS amplification.

![Fig. 2. (a) Experimental setup. (b) The optical spectrum of the OCS-SSB pump.](image)

The measured SBS gain spectra are shown in Fig. 3. The gain bandwidth was set at 500 MHz with 50 reconfigurable pump lines. Fig. 3 (a) and (b) are the SBS gain spectrum and phase response before implementing the feedback compensation. Fig. 3 (c) shows the flat electrical spectral lines generated by the AWG. Due to the non-ideal frequency response of the DPMZM and the PD, the pump lines became uneven and the corresponding SBS gain ripple was as high as ±2.5 dB (may even higher in wider bandwidth cases) accompanying remarkable unwanted gain out of the pass band. Meanwhile the curve of the phase response was quite rough due to the large amplitude ripple.

![Fig. 3. The original SBS gain spectrum (a), the phase response (b) and corresponding electrical spectral lines (c). The SBS gain spectrum (e), phase response (f) and corresponding electrical spectral lines (d) after feedback process.](image)
After implementing the feedback process for several times, we obtained the SBS gain spectrum shown in Fig. 3(e). The gain was about 25 dB and the maximum ripple was reduced to ±0.35 dB. In the meantime the cure of the phase response was very smooth as shown in (f). The 3-dB and 15-dB bandwidth were 493 MHz and 539 MHz respectively, corresponding to an SF_{15dB} of 1.093, which is close to the ideal rectangular case of 1. The corresponding electrical spectral lines are shown in (d), which are totally different from the original one in (c), thus proving the importance and validity of the feedback compensation method.

The bandwidth of this active filter can be easily set by changing the number of spectral lines in the AWG. Some other gain spectra and phase responses with different bandwidths are shown in Fig. 4. The range is from 10 MHz to 1 GHz, whose tuning resolution was determined by the electrical frequency spacing of 10 MHz. And the parameters of filters with wider bandwidth are listed in Table 1.

![Fig. 4. The gain spectra with different bandwidth of (a) 10 MHz (b) 50 MHz (c) 100 MHz (d) 200 MHz (e) 1 GHz and their corresponding phase response (f) ~ (j).](image)

<table>
<thead>
<tr>
<th>Bandwidth/MHz</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain/dB</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Ripple/dB</td>
<td>±0.49</td>
<td>±0.80</td>
<td>±1.05</td>
<td>±1.75</td>
<td>±1.85</td>
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In theory, the bandwidth of the filter is limited by the Brillouin frequency shift of ~10.8 GHz. When the bandwidth is narrow, the maximum gain can be very large. As the bandwidth increases, the power of each pump line becomes smaller with the same pump power, resulting in lower SBS gain. With the increase of the filter bandwidth meanwhile keeping the same gain, the pump power launched into the fiber increases tremendously thus causing remarkable nonlinear effects. The four-wave mixing (FWM) is the dominant effect which will reshape the pump line and generate new frequency components. The compensation method used in the experiment assumes that the pump light at a certain frequency is only related to the corresponding electrical spectral line which however, is not true when the FWM redistributes the pump power, thus the top flatness of the gain spectrum cannot be improved too much by the feedback compensation process. With a more suitable nonlinear compensation method and high efficient SBS fibers to improve the pump efficiency, the flatness can be further improved and a rectangular filter with wider bandwidth can be achieved.

4. Conclusion

We propose a narrowband rectangular optical filter based on stimulated Brillouin scattering with tunable bandwidth from 50 MHz to 3 GHz with a resolution of 10 MHz. A feedback compensation process is used to accurately control the amplitude of the pump lines and improve the top flatness and the edge steepness of the gain spectrum. The achieved shape factor is 1.093 and the gain ripple is ±0.35 dB at a 500-MHz gain bandwidth which is close to the ideal rectangular case. The proposed rectangular filters can find potential applications in optical/microwave signal processing fields.

5. References