GHz-wide Arbitrary-shaped Microwave Photonic Filter Based on Stimulated Brillouin Scattering Using Directly-modulated Laser

Wei Wei,[1,2] Lilin Yi,[1,*] Yves Jaouën,[2] Weisheng Hu[1]
[1]State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai, China
[2] LTCI CNRS, Télécom ParisTech, Université Paris Saclay, Paris, France
*lilinyi@sjtu.edu.cn

***Abstract*—We present a cost-efficient GHz-wide arbitrary-shaped microwave photonic filter based on stimulated Brillouin scattering in fiber. By employing a directly-modulated laser with well-designed current waveform and feedback adjustment, the filter shape has been arbitrarily controlled with high precision.**

***Keywords*—microwave photonic filter; stimulated Brillouin scattering; arbittary shaped filter**

I. INTRODUCTION

As a core microwave photonic component, the microwave photonic filter (MPF) has attracted consistent interests due to its prominent superiority in tunability and reconfigurability. The realization of the MPF can be roughly categorized into two main approaches: one type is delayed-tap based finite impulse response filter [1]; the other one is based on optical filter techniques to filter the RF-modulated optical signal directly [2]. For both approaches, the research trend is always to increase the flexibility while decreasing the cost.

Stimulated Brillouin scattering (SBS) is used for realizing MPFs thanks to its high selective amplification or absorption [3]. Previously, we have realized an arbitrary-shaped software-defined MPF with 15-MHz configurable resolution based on SBS effect in fiber [4]. Accurate Brillouin pump spectral control scheme has been demonstrated based on single sideband modulation to map the designed electrical spectrum onto the optical domain. However, this approach required an IQ modulator (IQM) with accurate bias control and a 90-degree hybrid coupler. In addition, an arbitrary waveform generator (AWG) with high sampling rate was necessary, which further raised the cost. Directly-modulated distributed feedback laser (DML) is a component widely used in cost-sensitive scenario. By adjusting the driving current, the spectrum of the DML can be controlled to some extent [5,6]. However, to the best of our knowledge, the precise control of the DML spectrum has not been demonstrated yet.

In this paper, we present the capability of arbitrarily controlling the shape of MPFs by using a low-cost DML. A bandwidth tunable rectangular MPF from 500 MHz to 2 GHz has been achieved with passband ripple of ~1.5 dB and 25 dB gain. The designed current waveform was generated by a digital-analog converter (DAC) with merely 1-GS/s sampling rate and was adjusted accurately with effective feedback algorithm. We also obtained arbitrary-shaped MPFs such as truncated Gaussian, super Gaussian, triangular and their inverse shapes. With multi-dimensional flexibility, the proposed MPF can find its versatile applications in microwave photonic fields. Compared with previous IQM approach, the DML-based approach provides similar performance but with lower complexity, which is preferable in cost-sensitive scenarios.

II. PRINCIPLE

It is well-known that the effective Brillouin gain spectrum for a broadband pump can be obtained by convolving the natural Brillouin gain with the pump spectrum. Thus as long as we can control the spectrum of the DML accurately and use it as the pump source, the Brillouin gain shape can be controlled precisely.

The control mechanism comprises two parts: the pre-design of current waveform based on filter shape target and accurate feedback adjustment as shown in Fig. 1. Different from a distributed Bragg reflector (DBR) based laser [7], the frequency modulation (FM) of a DML always accompanies amplitude modulation (AM). Moreover, the adiabatic chirp and transient chirp affect the laser spectrum in different manners [8]. For the waveform pre-design, we first assume the DML as a pure frequency modulator only affected by adiabatic chirp: a ramp waveform will lead to a continuous rectangular spectrum. The peak-to-peak voltage of the waveform defines the bandwidth of the MPF, which can be reconfigured easily. We also simply assume that the light intensity at a specific frequency is proportional to the time (shown as Δt for convenience) for which the current stays at the corresponding value (represented by V). Considering the exponential relation between the

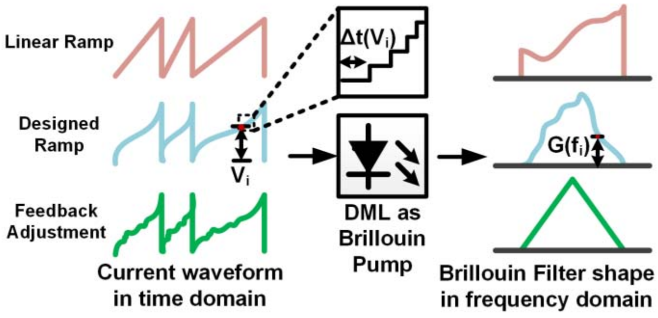

Fig. 1: Generating a triangular filter by adjusting the modulated current of a DML as Brillouin pump.

This work was supported by National Natural Science Foundation of China (61575122).

Brillouin gain (represented by G) and the pump power, the Brillouin gain in the unit of dB has a linear relation to the time Δt. Based on this relation, the waveform can be designed according to the targeted filter shape. For instance, for a triangular filter, a ramp with large slope at the two ends and small slope in the middle is needed as shown in Fig. 1.

Due to the non-ideal FM modulation, the designed waveform usually leads to an MPF with non-ideal shape. In the experiment, we found that when using a periodic ramp, there were peaks at the frequencies equaling the fixed period due to the AM effect, thus we use non-periodic ramp to make its spectrum continuous so as to suppress these peaks. The average duration of the ramps is 10 ns which is far smaller than the signal transmission time through the fiber (~60 μs), making the frequency swept pump equivalent to a broadband pump. Moreover, we propose a feedback algorithm for a more accurate adjustment. We first measure the filter shape by using an electrical vector network analyzer (EVNA). Then we calculate the new time duration Δt_{n+1} for each frequency component of the filter based on the relation between Brillouin gain and the previous time duration Δt_n of corresponding voltage value V_i as shown in (1):

$$\Delta t_{n+1}\left(V_i\right) = \Delta t_n\left(V_i\right) * \left(1 - EF * \frac{G_M\left(f_i\right) - G_T\left(f_i\right)}{G_M\left(f_i\right)}\right) \qquad (1)$$

where G_M and G_T are the measured and targeted gain at frequency f_i; the EF is an experience factor for controlling the convergence rate. After 5-10 iterations (related to the shape precision) of the feedback adjustment, the pump waveform for targeted shape can be obtained and this optimal waveform can be preserved for future use with no need for further feedback. Note that the central frequency of the proposed MPF can be easily changed by changing the wavelength of the DML thermally. Thus the proposed MPF provides flexibility on bandwidth, central frequency and most importantly filter shape at the same time.

III. EXPERIMENT AND RESULTS

The experimental setup is shown in Fig. 2. In the pump branch, a DML was driven by a well-designed current waveform generated with a DAC. After boosted by a high power erbium-doped fiber amplifier (EDFA), the modulated light was sent into a 12.5-km long single mode fiber (SMF) acting as the Brillouin pump. A polarization controller (PC) was used to maintain the SBS gain at the maximum value. An alternative solution is to use depolarized pump to make the SBS gain polarization insensitive [9]. In the probe branch, a swept signal covering the whole SBS gain region was generated by an EVNA. It modulated the CW light in a Mach-Zehnder modulator (MZM) to generate the probe signal. After suppression of the high-frequency sideband by a narrowband fiber Bragg grating (FBG), the probe light propagated through the fiber and was amplified when it swept within the SBS gain region as shown in the inset. Then the probe signal was detected by a photodiode (PD) and was sent into the EVNA, where the amplitude and phase response were measured. The SBS gain spectra were obtained by comparing the results when the SBS pump was On and Off. Compared with the external modulation using 90-degree hybrid coupler, expensive IQM and accurate bias control, the structure here is much simpler and more cost-efficient.

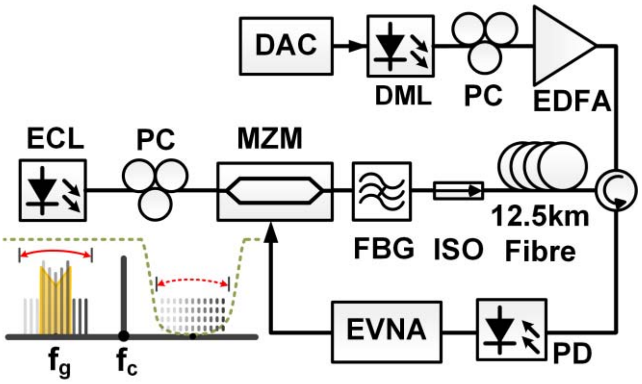

Fig. 2: Experimental setup

The rectangular filters with tunable bandwidth are demonstrated in Fig. 3. By changing the amplitude of the current waveform, the filter bandwidth was easily reconfigured from 500 MHz to 2 GHz. The sampling rate of the DAC was set to 1 GS/s. As shown in Fig. 3(a) and 3(b), all the amplitude responses of the filters had steep edges and flat passband. The passband ripple was controlled within 1.5 dB leading to smooth phase responses. The feedback process is shown in Fig. 3(c). With only 7 iterations using the well-designed feedback adjustment, the passband ripple was decreased from 6.6 dB to 1.4 dB. The 10 GS/s case is also shown for comparison. The ripple value of these two cases was similar after feedback process. The current waveforms and corresponding filter shapes are also demonstrated in the insets. The initial linear ramp resulted in an unflattened passband, while the adjusted ramp led to flat-top shape, which proved the validity of the accurate feedback process. Although the sampling rate of the DAC was set to merely 1 GS/s, the filter bandwidth reached 2 GHz and can be further extended, which is limited theoretically by the Brillouin frequency shift of ~11 GHz in fiber.

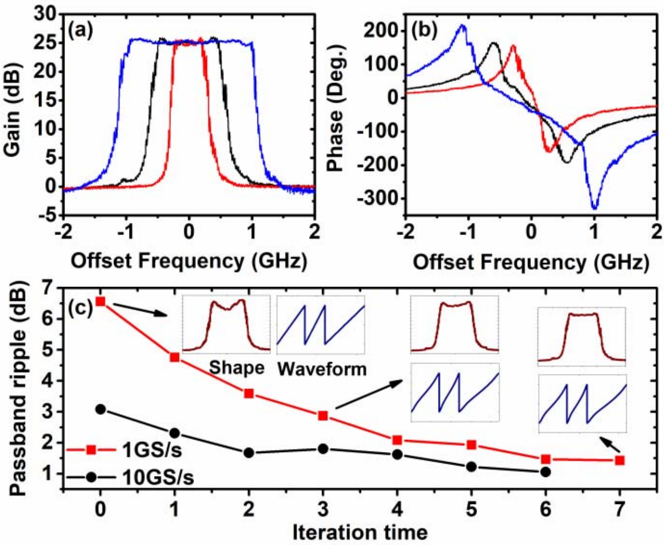

Fig. 3: The (a) amplitude and (b) phase response of rectangular MPFs. (c) Typical convergence process with corresponding current waveforms and filter shape

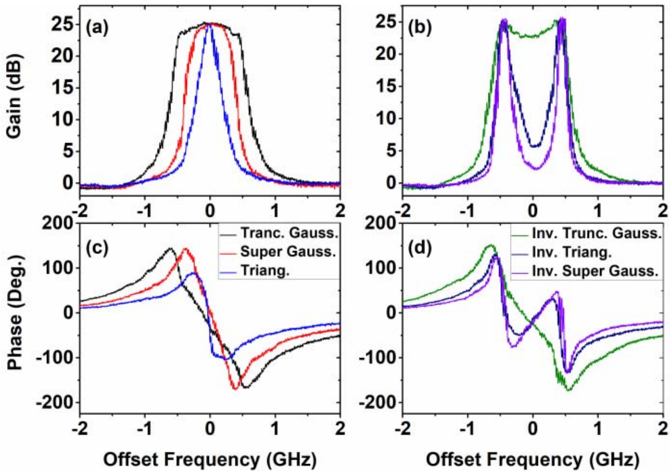

Fig. 4: The (a, b) amplitude and (c, d) phase response of arbitrary-shaped optical filters

The filter shape can also be defined precisely showing the superiority of the proposed approach. In order to increase the control precision, we used 10-GHz sampling rate of the DAC. By using well-designed current waveforms and applying the feedback adjustment according to the targeted filter shape, the final MPF shapes are obtained as shown in Fig. 4, including truncated-Gaussian, super-Gaussian, triangular and their inverse shapes. The corresponding phase response was different, which was dependent on the specific filter amplitude response. It should be noted that the control precision of the filter shape is also related to the stability of the DML laser. A stable and less drifting laser is expected if high shape fidelity is required.

We compared the rectangular filter generated by DML approach with the previous IQM approach as shown in Fig. 5. The DML approach resulted in similar passband ripple and slightly less steep edges which is acceptable for most of the applications. However, the external modulation approach requires expensive IQM with high complexity setup and it needs a DAC with the sampling rate equaling at least two times of the filter bandwidth. While the DML solution needs no modulator and has less requirement for the DAC, thus making it an ideal solution for cost-efficient filter generation and instrumentation.

IV. CONCLUSIONS

We have presented a cost-efficient arbitrary-shaped MPF solution. Instead of using complicated IQM setup and high sampling rate DAC, we use a DML with well-design current waveform and accurate feedback adjustment. The rectangular filters with bandwidth from 500 MHz to 2 GHz and ~1.5 dB passband ripple have been obtained by using 1-GS/s sampling rate DAC. Other filter shapes have also been demonstrated with high shape fidelity. The comparison between the proposed DML approach with the previous IQM method shows that the two solutions have similar performance but the DML approach has much simpler structure and lower requirements for the DAC, which is more suitable for cost-sensitive microwave photonic or optical applications.

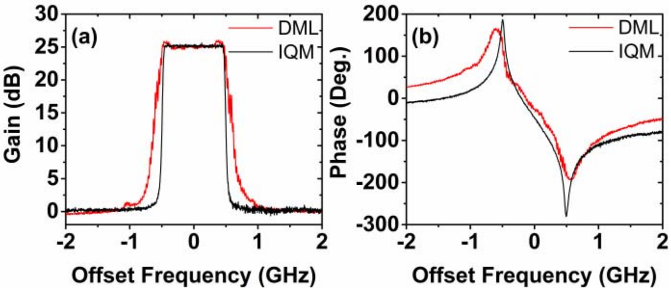

Fig. 5: The comparison between current modulation with a DML and external modulation with an IQM.

REFERENCES

[1] J. Palaci, G. E. Villanueva, J. V. Galan, J. Marti, and B. Vidal, "Single bandpass photonic microwave filter based on a notch ring resonator," IEEE Photonic. Tech. L., vol. 22, pp. 1276-1278, September 2010.

[2] S. Xiao and A. M. Weiner, "Coherent photonic processing of microwave signals using spatial light modulators: Programmable amplitude filters," J. Lightwave Technol., vol. 24, pp. 2523-2529, July 2006.

[3] B. Vidal, M. A. Piqueras and J. Marti, "Tunable and reconfigurable photonic microwave filter based on stimulated Brillouin scattering," Opt. Lett., vol. 32, pp. 23-25, January 2007.

[4] W. Wei, L. Yi, Y. Jaouën, and W. Hu, "Software-defined microwave photonic filter with high reconfigurable resolution," Sci. Rep., vol. 6, p. 35621, October 2016.

[5] A. Zadok, A. Eyal and M. Tur, "Gigahertz-wide optically reconfigurable filters using stimulated brillouin scattering," J. Lightwave Technol., vol. 25, pp. 2168-2174, August 2007.

[6] E. Cabrera-Granado, O. G. Calderon, S. Melle, and D. J. Gauthier, "Observation of large 10-Gb/s SBS slow light delay with low distortion using an optimized gain profile," Opt. Express, vol. 16, pp. 16032-16042, September 2008.

[7] J. O. White, A. Vasilyev, J. P. Cahill, N. Satyan, O. Okusaga, G. Rakuljic, C. E. Mungan, and A. Yariv, "Suppression of stimulated Brillouin scattering in optical fibers using a linearly chirped diode laser," Opt. Express, vol. 20, pp. 15872-15881, July 2012.

[8] L. A. Coldren, S. W. Corzine, M. L. Mashanovitch. Diode lasers and photonic integrated circuits, 2nd ed., John Wiley & Sons, 2012, pp.270-275.

[9] L. Yi, W. Wei, Y. Jaouen, M. Shi, B. Han, M. Morvan, and W. Hu, "Polarization-independent rectangular microwave photonic filter based on stimulated Brillouin scattering," J. Lightwave Technol., vol. 34, pp. 669-675, January 2016.