Coherent Photonic RF Channelization Based on Stimulated Brillouin Scattering

Weiyuan Xu, Dan Zhu* and Shilong Pan*
Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education
Nanjing University of Aeronautics and Astronautics
Nanjing 210016, China
*Corresponding author: danzhu@nuaa.edu.cn, pans@ieee.org

Abstract—A novel high-resolution channelizer based on dual coherent optical frequency combs (OFCs) and stimulated Brillouin scattering (SBS) is proposed and demonstrated. In the proposed scheme, the frequency components of a wideband RF signal are sliced into a number of parallel parts and converted into signals with the same center frequency. The bandwidth of each frequency slice is determined by the gain bandwidth of the SBS (tens of MHz), and all the information in the RF signal is retained after the channelization. An experiment is carried out. Photonic RF channelization with channel spacing of 80 MHz and a crosstalk suppression of more than 16.79 dB is realized.

Index Terms—Microwave photonics, channelization, optical frequency comb, stimulated Brillouin scattering.

I. INTRODUCTION

RF receivers with high frequency and large bandwidth are increasingly desired in modern radar [1], electronic warfare [2] and communication satellite [3]. To handle the broadband signal with bandwidth-limited analog-to-digital converters (ADCs), it is essential to channelize the broadband signal into a number of frequency channels with small bandwidths. Recently, implementing the RF channelization in the optical domain has attracted great interests thanks to the advantages in terms of large bandwidth, flat frequency response, good isolation, and immunity to electromagnetic interference brought by the photonic technologies [4-10].

Several photonic-assisted channelizers have been proposed [4-10]. One approach is to modulate the RF signal on an optical carrier, and then split it into several consecutive channels by using an array of narrowband optical filters [4]. However, the narrowband optical filter array should have precise center frequencies and identical bandwidth (typically less than 1 GHz), which is very difficult to be fabricated. Another approach is to modulate the RF signal on an optical frequency comb (OFC) [5, 6] to create an array of copies of the RF signal. Then, a periodic optical filter (such as Fabry-Pérot filters [5] and integrated ring resonators [6]) with a free spectral range (FSR) that is slightly different from the frequency spacing of the OFC is used to select different frequency components around different comb lines. Based on these operations, a wavelength division de-multiplexer can effectively split the RF signal into a large number of frequency channels. These methods, however, can only indicate the frequency band of the RF signal, while the information carried by the RF signal is lost. To solve this problem, a coherent photonic RF channelizer was proposed based on a free-space diffraction grating [7], in which different frequency components in the optical microwave signal are spatially split into consecutive channels and in each channel an optical comb line with a constant frequency difference to the center frequency of the channel is inserted. After photodetection, every portion of the RF signal spectrum is translated to the same IF band by which the information is fully preserved. However, the system performance is affected by the wavelength drift of the diffraction grating or the optical microwave signal. To remedy this, coherent channelization based on two coherent OFCs and digital I/Q demodulation was proposed to introduce the advantage of high frequency resolution and high crosstalk suppression through the employment of digital signal processing [8]. But precise phase and amplitude match between I and Q tributaries is required in each channel, which can be mitigated by using polarization I/Q demodulation in [9]. On the other hand, the stimulated Brillouin scattering (SBS) effect in optical fibers can form an optical active filter with a response profile controlled by the pump light, which can be used to serve as the narrowband optical filters in a coherent channelizer [10]. However, a number of microwave sources with designated frequencies are required to create the desired frequency shifts for slicing the RF signal, so the system would be cumbersome with unaffordable cost. In addition, the signals after channelization are still in the RF band, which requires additional local oscillators (LOs) to perform downconversion.


In this Letter, we propose and demonstrate a new coherent photonic RF channelizer with high resolution based on dual coherent OFCs and SBS effect in optical fiber. In the proposed
scheme, two coherent OFCs with different FSRs are used. An array of copies of the RF signal is created in the optical domain using one OFC (signal OFC), and a periodic bandpass optical filter is formed by the other OFC (local OFC) based on the SBS effect in a length of high-nonlinear fiber (HNLF). Due to the FSR difference of the two OFCs, when the signal OFC is injected into the periodic bandpass optical filter formed by the local OFC, different frequency components of the RF signal are selected around different comb lines of the signal OFC. Then, the SBS-amplified signal OFC is combined with a portion of the local OFC, wavelength demultiplexed and coherently detected by an array of photodetectors (PDs). Since the two OFCs are generated from the same LD, the wavelength drifts of the optical RF signal and the filter are the same. Only two microwave frequencies are required for the entire system, and all the RF signal spectrum is translated to the same IF band, making the system relatively compact and cost effective. An experiment is carried out. Photonic RF channelization with channel spacing of 80 MHz and a crosstalk suppression of more than 16.79 dB is realized.

II. PRINCIPLE

Fig. 1 shows the scheme of the proposed SBS-based coherent channelizer. Signal OFC with FSR of $\delta_{\text{sig}}$ and local OFC with FSR of $\delta_{\text{lo}}$ are generated from the same LD seed by modulating single-tone RF signals with frequency of $\delta_{\text{sig}}$ and $\delta_{\text{lo}}$ at the corresponding PolMs, respectively [11]. The signal OFC is modulated by the RF signal to be channelized through a Mach-Zehnder modulator (MZM) being biased at the double-sideband carrier-suppressed (DSB-CS) point and then introduced to a length of HNLF. On the other path, the local OFC is used as pump source to realize the SBS gain effect acting on the modulated RF signal in the HNLF. The SBS-amplified signal is combined with the reflected part of local OFC and then de-multiplexed. As shown in Fig. 2, due to the difference of FSRs of the two OFCs, different frequency components of the RF signal are selected around different comb lines of the signal OFC in each channel, corresponding to one comb line of the local OFC. The optical signal in each channel gets detected coherently in PD to realize the channelized information output.

The frequency of each comb line of the signal OFC can be expressed as

$$f_{\text{sig}}(k) = f_{\text{sig}}(1) + (k - 1)\delta_{\text{sig}}$$

(1)

where $f_{\text{sig}}(1)$ is the frequency of the first line. Considering that the MZM is driven by a RF signal of $f_{RF}$ under DSB-CS condition, the RF signal is multicast by the signal OFC and the $k$th multicast copy is as follows

$$f_{\text{up-sig}}(k) = f_{\text{sig}}(1) + (k - 1)\delta_{\text{sig}} + f_{RF}$$

(2)

The red-shifted copies are ignored as they cannot be amplified by the SBS effect when the frequency of each comb line in the local OFC is higher than that of the corresponding comb line in the signal OFC. $0 < f_{RF} < \frac{\delta_{\text{sig}}}{2}$ or $\frac{\delta_{\text{sig}}}{2} < f_{RF} < \delta_{\text{sig}}$ should be always satisfied to avoid the spectrum aliasing. Thus the bandwidth limitation for the RF signal to be channelized is $\delta_{\text{sig}}/2$.

On the other hand, the center frequency of SBS gain response corresponding to the $k$th comb line of the local OFC is expressed as

$$f_{c}(k) = f_{c}(1) + (k - 1)\delta_{c} - v_{g}$$

(3)

where $v_{g}$ is the SBS frequency shift. The profile of the SBS gain response is expressed as [12]:

$$S(f, k) = \exp\left(\frac{G(\Gamma/2)^2}{(f - f_c(k))^2 + (\Gamma/2)^2}\right)$$

(4)

where $\Gamma$ is the full-width at half maximum (FWHM), $G$ is the exponential SBS gain. Considering that each line of the local OFC has equal power, each channel has the same gain.

Fig. 2. Principle of the photonic channelization based on dual coherent OFCs and SBS. (a) The signal OFC and local OFC. (b) The DSB-CS modulated signal OFC. (c) The extraction of different spectrum slices of the RF signal in each channel based on the SBS gain pumped by local OFC.

Only part of the $k$th copy passes the corresponding $k$th SBS gain peak and is output at the $k$th channel of the de-mux. The center frequency of the selected RF signal in the $k$th channel is

$$f_{\text{out}}(k) = f_{\text{sig}}(1) - \delta_{\text{sig}}(1) - v_{g} + (k - 1)\delta_{\text{SR}}$$

(5)

where $\delta_{\text{SR}} = \delta_{\text{lo}} - \delta_{\text{sig}}$ is the FSR difference of the signal OFC and the local OFC. And the intensity of the output optical-carried RF signal in the $k$th channel is as follows:

$$I_{\text{RF}}(f_{\text{RF}}, k) = I_{0}(f_{\text{RF}}, k)\exp\left(\frac{G(\Gamma/2)^2}{(f_{\text{RF}} - f_{c}(k))^2 + (\Gamma/2)^2}\right)$$

(6)

where $I_{0}$ refers to the intensity of the optical-carried RF signal before amplified.

By using an optical de-mux, the SBS amplified optical-carried RF signal coupled with the $k$th line of reflected local OFC from the mirror is introduced to a PD and the corresponding channelized information is output with the center frequency of $v_{g}$. In this way, all the frequency components of the RF signal are sliced into a number of parallel parts and converted into signals with the same center frequency of $v_{g}$. Thanks to the coherence of signal OFC and local OFC, no information is missed. Thus, a coherent photonic RF channelizer is realized.

III. EXPERIMENTAL RESULTS AND DISCUSSION

An experiment based on the setup shown in Fig.1 is performed. The dual coherent OFCs are generated by splitting a continuous-wave light (TeraXion PS-_DLL) at 1550.095 nm to two branches as the coherent seeds, each is fed into a polarization modulator (PolM, Versawave, 40 GHz) and modulated by the microwave tone with the frequency of $\delta_{\text{sig}} = 21.28$ GHz and $\delta_{\text{lo}} = 21.20$ GHz, respectively. The dual coherent OFCs of five lines with the FSR of 21.28 GHz and
21.20 GHz in the up- and down-branch are realized [11]. The microwave tones are generated by two microwave signal generators (Agilent E8257D), and amplified by two electrical amplifiers (EA, Agilent 83020A, 2-26.5 GHz, 30-dB gain). The two-tone RF signal used to analyze the channelization character is generated through combining two signals generated by Agilent E8267D and Anritsu MP1763C, respectively. The local OFC is amplified by an erbium-doped fiber amplifier (EDFA) and led to 1-km length of high nonlinear dispersion-shifted fiber (HNLDSSF) through a circulator as Brillouin pump waves. A fiber mirror is used to reflect part of the local OFC through the circulator to function as local carriers of coherent detection. A tunable optical filter (Yenista XTM-50) is used as the de-mux to separate the channels. The electrical spectra are measured by an electrical spectrum analyzer (ESA, Agilent N9030A). An optical spectrum analyzer (OSA, Yokogawa AQ 6370C) with a resolution of 0.02 nm is used to monitor the optical spectrum. The SBS gain response is measured with a vector network analyzer (VNA, Agilent N5230A).

The Brillouin frequency shift \(v_B\) and the SBS gain response of the HNLDSSF based on the OVNA method [13]. TLS: tunable laser, OVNA: optical vector network analyzer. (b) Measured SBS gain response.

The Brillouin frequency shift \(v_B\) and the SBS gain response of the HNLDSSF with the local OFC comb lines as the pumping are measured based on the optical vector network analyzer method [13] shown in Fig. 4 (a). The measured SBS response is shown in Fig. 4 (b). We can see that the Brillouin frequency shift \(v_B\) is 9.19 GHz, the 3-dB and 15-dB gain bandwidth is 43.99 MHz and 141.02 MHz, respectively, which results in the 15-dB shape factor of 3.206 (defined as the ratio of the 15-dB to 3-dB bandwidth [14]), which determines the crosstalk of the channelizer. The shape factor of the response determines the crosstalk between channels, which can be improved by utilizing digital feedback control of the pump spectrum [14]. And based on our proposed scheme, all channels can be adjusted simultaneously, which ensures the system’s simplicity and flexibility.

According to (5), with the value of \(f_{(1)}-f_{(1)}\) to be 21.36 GHz, \(v_B\) to be 9.19 GHz, and FSR difference of \(\Delta f\) to be 80 MHz, channelization with 4 channels will be obtained with the 1st to 4th channel’s corresponding center frequencies being 12.17 GHz, 12.09 GHz, 12.01 GHz and 11.93 GHz, respectively. In order to describe the multiple frequency channelization, one-RF signal with frequencies of 12.08 GHz and 11.92 GHz at the same power is input to be channelized. The measured electrical spectra of each channel within 18-GHz span and 800-MHz span are shown in Fig. 5 (a)-(h), respectively. As can be seen in the spectra with 18-GHz span, harmonic waves can be seen in the spectra due to the square law of PD and nonideal shape of the optical filter. Clearly, the RF tone of 12.08 GHz can be observed in the 2nd channel as shown in Fig. 5 (c) and (d) within 18-GHz and 800-MHz span, respectively, while the RF tone of 11.92 GHz can be observed in the 4th channel as shown in Fig. 5 (g) and (h). The signals are both converted into the signals with the same center frequency of 9.19 GHz. For the two RF tones separated by 160 MHz, the channel crosstalk suppression rate is 19.37 dB and 16.79 dB with the 2nd and 4th channel, respectively, which is determined by the shape of the SBS gain. Meanwhile, for the 1st and 3rd channels in which no RF components is located in, no obvious RF tone can be seen. Thus channelization with channel spacing of 80 MHz and crosstalk
more than 16.79 dB is realized. The channelization center frequency, channel spacing can be tuned by adjusting the two OFCs’ FSRs of $\delta_{lo}$ and $\delta_{sig}$.

![Diagram](image_url)

**Fig. 5.** Measured spectrum of 1st channel in (a) 18-GHz span, (b) 0.8-GHz same center frequency to avoid the using of additional crosstalk suppression of more than 16.79 dB is realized. The channelization center frequency, channel spacing can be tuned by adjusting the two OFCs’ FSRs of $\delta_{lo}$ and $\delta_{sig}$.

![Diagram](image_url)

**Fig. 5 (continued).** Measured spectrum of 4th channel in (g) 18-GHz span, (h) 0.8-GHz span; 2nd channel in (c) 18-GHz span, (d) 0.8-GHz span; 3rd channel in (e) 18-GHz span, (f) 0.8-GHz span; 4th channel in (g) 18-GHz span, (h) 0.8-GHz span, with corresponding channel RF center frequencies are 12.17 GHz, 12.09 GHz, 12.01 GHz and 11.93 GHz, separately. (e) The received electrical power in each channel.

IV. CONCLUSION

A novel high-resolution channelization based on dual coherent OFCs and SBS effect is proposed and experimentally demonstrated. An experimental demonstration of channelization with channel spacing of 80 MHz and a crosstalk suppression of more than 16.79 dB is realized. The frequency components of a wideband RF signal are sliced into a number of parallel parts and converted into signals with the same center frequency to avoid the using of additional different LOs to perform downconversion in each channel for subsequent processing. Only two microwave frequencies are required for the entire system and no individual tuning is involved in each channel, which makes the system simple and flexible.

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