Photonic-Assisted Microwave Channelizer With Improved Channel Characteristics Based on Spectrum-Controlled Stimulated Brillouin Scattering

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***Abstract*—A photonic-assisted microwave channelizer with improved channel characteristics based on spectrum-controlled stimulated Brillouin scattering (SBS) is proposed and experimentally demonstrated. In the proposed system, N lightwaves from a laser array are multiplexed and then split into two paths. In the upper path, the lightwaves are modulated by a microwave signal with its frequency to be measured. In the lower path, for each lightwave, the wavelength is shifted to a specific shorter wavelength via carrier-suppressed single-sideband modulation and the spectrum is then shaped. The wavelength-shifted and spectrum-shaped lightwaves are used to pump a single-mode fiber to trigger SBS. Thanks to the SBS effect, multiple gain channels at the N wavelengths are generated. The channel profile of each channel, determined by the designed spectral shape of the pump source, is improved with a flat top and a reduced shape factor. The characteristics including the bandwidth, channel spacing, and channel profile can be controlled by adjusting the spectral shape of the pump source. A proof-of-concept experiment is performed. A microwave channelizer with a shape factor less than 2, a tunable channel bandwidth of 40, 60, or 90 MHz, and a tunable channel spacing of 50, 70, or 80 MHz, is demonstrated.**

***Index Terms*—Channel characteristics, microwave channelizer, microwave frequency measurement, microwave photonics, shape factor, stimulated Brillouin scattering (SBS).**

I. INTRODUCTION

MICROWAVE frequency analysis and measurement plays a significant role in the field of electronic warfare, where the recognition and the classification of the frequency of a radar or communication signal is one of the major tasks [1]. A challenge facing the operations is that the system should be able to perform the recognition and the classification of RF signals in a wide-open frequency range. With the development of microwave photonics technologies [2], [3], frequency analysis and measurement based on photonics has been regarded as a powerful alternative for wideband operations. In general, photonic-assisted microwave frequency analysis and measurement can be implemented based on: 1) a channelizer [4]–[14]; 2) frequency-to-amplitude mapping [15]–[18]; 3) frequency-to-time mapping; and 4) frequency sweeping [19]–[21]. Among these approaches, the ones based on an optical or photonic-assisted channelizer have the ability to instantaneously and simultaneously discriminate multiple frequency components or multiple signals. In [5] and [6], the microwave channelizer was implemented via the spectral-to-spatial conversion using a diffraction grating or an integrated Fresnel lens. While in [4] and [7]–[13], optical filters, which could be phase-shifted fiber gratings, ring resonators, or etalons, were used to perform frequency filtering in the optical domain for the microwave channelizer. However, there is an obvious tradeoff between the channel bandwidth and the shape factor of channels. The shape factor here is defined as a ratio between the 20-dB bandwidth and the 3-dB bandwidth of a channel and a value close to 1 indicates an ideal rectangular profile of channels. In other words, the channel bandwidth is usually greater than 1 GHz in the case of an excellent shape factor or the shape factor is more than 4 for a channel bandwidth of a few hundred megahertz or tens of megahertz due to the Lorentzian shape resulting from high-finesses etalons or fiber gratings with a single phase shift. It is difficult to simultaneously achieve a quasi-rectangular channel with a flat top and a bandwidth of tens of megahertz in the optical domain. Thus, the key limitation of using an optical or photonic-assisted channelizer for microwave frequency analysis and measurement is poor accuracy since the channel characteristics including the bandwidth, channel spacing, and channel profile are difficult to control to simultaneously meet the needs for accurate frequency measurement. Moreover, the channel bandwidth and the channel profile are mostly regarded to be fixed once the optical filters are fabricated, which might be a big obstacle for the reconfiguration and the tuning of the microwave channelizer.

Recently, the stimulated Brillouin scattering (SBS) effect has been widely employed to perform microwave signal processing in the optical domain. A key feature of the SBS is that its gain

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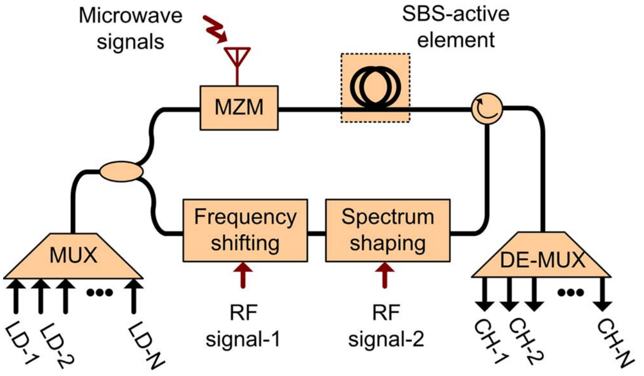


Fig. 1. Schematic diagram of the proposed microwave channelizer (laser diode: LD; multiplexer: MUX; Mach–Zehnder modulator: MZM; de-multiplexer: DE-MUX; channel: CH).

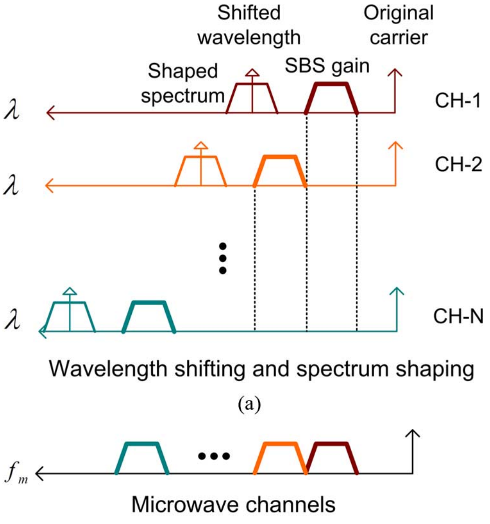
spectrum has an ultra-narrow bandwidth of tens of megahertz [22]–[27], which is much narrower than that of a conventional optical filter. Thus, the use of the SBS effect would provide an effective solution to generate an ultra-narrow bandwidth. However, for applications such as microwave channelization, due to the Lorentzian shape of the gain spectrum, the shape is too poor to be used directly.

In this paper, a photonic-assisted microwave channelizer with significantly improved channel characteristics is proposed and demonstrated. The key contribution of the proposed channelizer is that a spectrum-controlled pump source is generated and then is used to produce the SBS effect in an optical fiber such that the resulting SBS gain spectrum is controlled to have a flat top and a reduced shaper factor. The proposed approach is experimentally demonstrated. A microwave channelizer with a channel bandwidth of 40, 60, or 90 MHz, a channel spacing of 50, 70, or 80 MHz, and a shape factor of less than 2 is demonstrated. Such a microwave channelizer could be used for many high-resolution applications.

II. PRINCIPLE

A. Photonic-Assisted Microwave Channelizer

The proposed microwave channelizer with N microwave channels is illustrated in Fig. 1. N lightwaves from an array of N laser diodes (LDs) are multiplexed at a multiplexer (MUX) and each wavelength-division-multiplexing (WDM) channel corresponds to one microwave channel. The multiplexed lightwaves are then split into two paths. In the upper path (i.e., the signal path), the lightwaves are externally modulated by the microwave signals with their frequencies to be measured. There is also an SBS-active element in the path, which can be a single-mode fiber (SMF), a dispersion-compensating fiber, or a highly nonlinear fiber. In the lower path (i.e., the pump path), for each lightwave, the wavelength is frequency shifted by applying an RF signal to a Mach–Zehnder modulator (MZM) to achieve carrier-suppressed single-sideband (CS-SSB) modulation and then the spectrum is shaped. The spectrum shaping on the pump source to produce the SBS effect can be trance back to [23]. The frequency-shifted and spectrum-shaped lightwaves are injected to pump the SBS-active element. Due to spectrum-controlled SBS effect, N gain channels with well-controlled spectral shape at the N wavelengths are generated in the optical domain. These gain channels are separated at a de-multiplexer (DE-MUX) and detected by N photodetectors. Thus, a microwave channelizer with N channels is implemented.



(a)

(b)

Fig. 2. Illustration of the operation of the proposed microwave channelizer. (a) Optical wavelength shifting and spectrum shaping and (b) channels of the microwave channelizer.

Two key steps are involved in implementing the proposed channelizer: the frequency shifting and the spectrum shaping of the SBS pump source. Fig. 2 shows the operations of the two steps. To implement the frequency shifting, the wavelength of each lightwave is shifted to a specified lower wavelength via CS-SSB modulation. The shifted lightwave is then spectrally shaped, a key step to ensure a gain channel with improved channel characteristics. The wavelength-shifted and spectrum-shaped lightwaves in the lower path are amplified and inputted into the SBS-active element via an optical circulator.

Thus, a spectrum-controlled SBS is formed at each WDM channel in the backward direction. The details will be presented in Section II-B. As shown in Fig. 2(a), the SBS gain spectrum is about 11 GHz away from the wavelength-shifted lightwave in each channel. Here, the wavelength shifts of the WDM channels are gradually increased, to form a specific channel spacing among the generated SBS gain spectra. Thus, an equivalent microwave channelization is achieved, as shown in Fig. 2(b). The operating frequency is equal to the wavelength offset between the central wavelength of the SBS gain spectrum and the output wavelength of the corresponding LD.

In addition, versatile channel profiles or channel arrangements can also be realized. Based on the spectrum-controlled SBS, uniform and flat-top channels with tunable bandwidth can be generated, as shown in Fig. 3(a) and (b). Other user-defined channel profiles, such as a triangular profile shown in Fig. 3(c), nonuniform channel bandwidth shown in Fig. 3(d), can be generated. This is an attractive channel arrangement, which can find applications such as a Wavelet transform where the

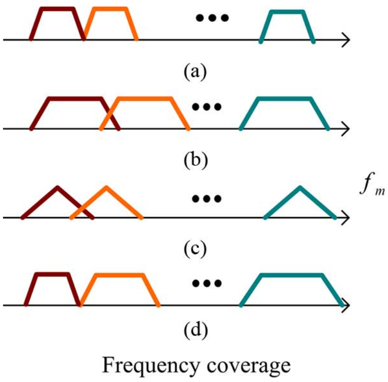


Fig. 3. Different channel profiles or channel arrangements of the proposed channelizer. (a) and (b) Flat-top channels with different bandwidths, but uniform spacing. (c) Triangular channels. (d) Flat-top channels with different bandwidths.

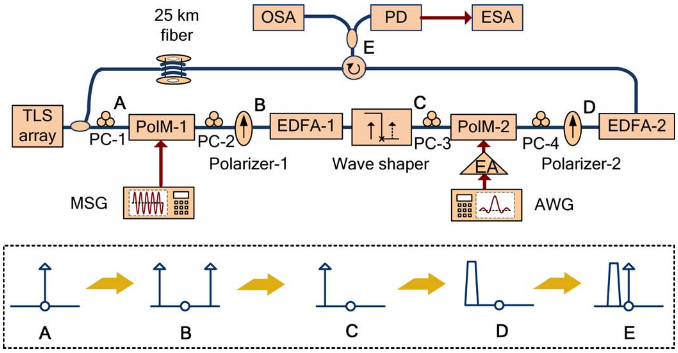


Fig. 4. Experimental setup for the proposed microwave channelizer and the demonstration of the desirable optical spectra in the setup (tunable laser source: TLS; polarization controller: PC; polarization modulator: PolM; erbium-doped fiber amplifier: EDFA; electrical amplifier: EA; microwave signal generator: MSG; arbitrary waveform generator: AWG; photodetector: PD; electrical spectrum analyzer: ESA; optical spectrum analyzer: OSA).

window functions can be scaled to achieve multi-resolution signal analysis.

B. Spectrum-Controlled SBS Gain

It is well known that the SBS in an optic fiber can provide an intrinsic gain spectrum with a 3-dB bandwidth as narrow as tens of megahertz [28]–[30]. Such a bandwidth is small enough for the implementation of a microwave channelizer with a high resolution. However, the key limitation of a direct use of the SBS gain spectrum is the poor spectral shape, which is Lorentzian, thus a large shape factor is usually resulted. Since the SBS gain spectrum is dominantly determined by the spectral shape of the pump source, to increase the top flatness and reduce the shape factor, an effective solution is to shape and control the spectrum of the SBS pump source. This is the reason that the spectrum shaping is the key step to ensure an improved channel profile, as mentioned in Section II-A.

Compared with a monochromatic lightwave, the spectrum-shaped pump source is more complex and the employment of a spectrum-shaped pump source would generate an SBS gain profile that is no longer Lorentzian [30]. Mathematically, the SBS spectral shape can be described as the convolution of the intrinsic SBS gain spectrum and the power spectrum of the pump

$$\begin{aligned} g(\omega) &= g_0(\omega) * I_p(\omega_p) \\ &= \int_{-\infty}^{+\infty} \frac{g_0 I_p(\omega_p)}{1 - i(\omega + \Omega_B - \omega_p)/(\Gamma_B/2)} d\omega_p \end{aligned} \tag{1}$$

where $g(\omega)$ is the complex gain function, $g_0(\omega)$ is the intrinsic SBS gain spectrum, $I_p(\omega_p)$ is the power spectrum of the pump, g_0 is the peak gain coefficient for a monochromatic pump, Ω_B is the Brillouin frequency shift, ω_p is the angular frequency of the pump, Γ_B is the intrinsic SBS resonance linewidth, and $*$ represents the convolution operation. Here, the SBS gain profile is just the real part of $g(\omega)$.

According to (1), two types of pumps can be employed to achieve a microwave channel having a desirable SBS gain profile. One should be a lightwave with a flat-top power spectrum and the other should be an optical comb with a comb spacing of tens megaherz. For the latter, when an optical comb with n comb lines and a spacing of $\Delta\Omega$ serves as the SBS pump, each comb line is considered as a monochromatic pump. The resulting SBS gain profile is given by

$$\begin{aligned} g(\omega) &= \sum_{k=0}^{n-1} \mathrm{Re}\left\{ \frac{g_0 I_k \times \Gamma_B/2}{\Gamma_B/2 - i[\omega + \Omega_B - (\omega_{p0} + k\Delta\omega)]} \right\} \\ &= \sum_{k=0}^{n-1} \frac{g_0 I_k (\Gamma_B/2)^2}{(\Gamma_B/2)^2 + [\omega + \Omega_B - (\omega_{p0} + k\Delta\omega)]^2} \end{aligned} \tag{2}$$

where I_k is the power of the kth comb line in the pump, and $\mathrm{Re}\{\cdot\}$ represents the real part. It can be deduced from (2) that the spectrum of the SBS gain can be easily controlled by tuning the number, the spacing, and the amplitude of the comb lines in the pump source, to achieve a channelizer with enhanced channel characteristics, including flat-top, reduced shape factor, tunable bandwidth, and channel spacing.

III. EXPERIMENT AND DISCUSSIONS

A. Improved Channel Profile

A proof-of-concept experiment is then performed to validate the proposed approach. The experimental setup is shown in Fig. 4, where the pump path consists of two polarization modulators (PolMs) to perform wavelength shifting and spectrum shaping. The lightwaves from two four-port tunable laser sources (TLSs) (Agilent 7714A), serving as the light sources of the WDM channels, are coupled into PolM-1. By applying an RF signal from a microwave signal generator (MSG) to PolM-1, at the output of Polarizer-1, the optical carrier in each WDM channel is suppressed, resulting in the generation of two first-order sidebands. A WaveShaper (Finisar 4000S) is then used to filter out the $+1$ st sideband while keeping the -1st sideband, thus the CS-SSB modulation is achieved. Since the frequency shift for each WDM channel is exactly equal to the frequency of the applied microwave signal, a high accuracy up to a few kilohertz can be simply achieved for the frequency shifting and a fast tuning of the frequency shift can be easily realized.

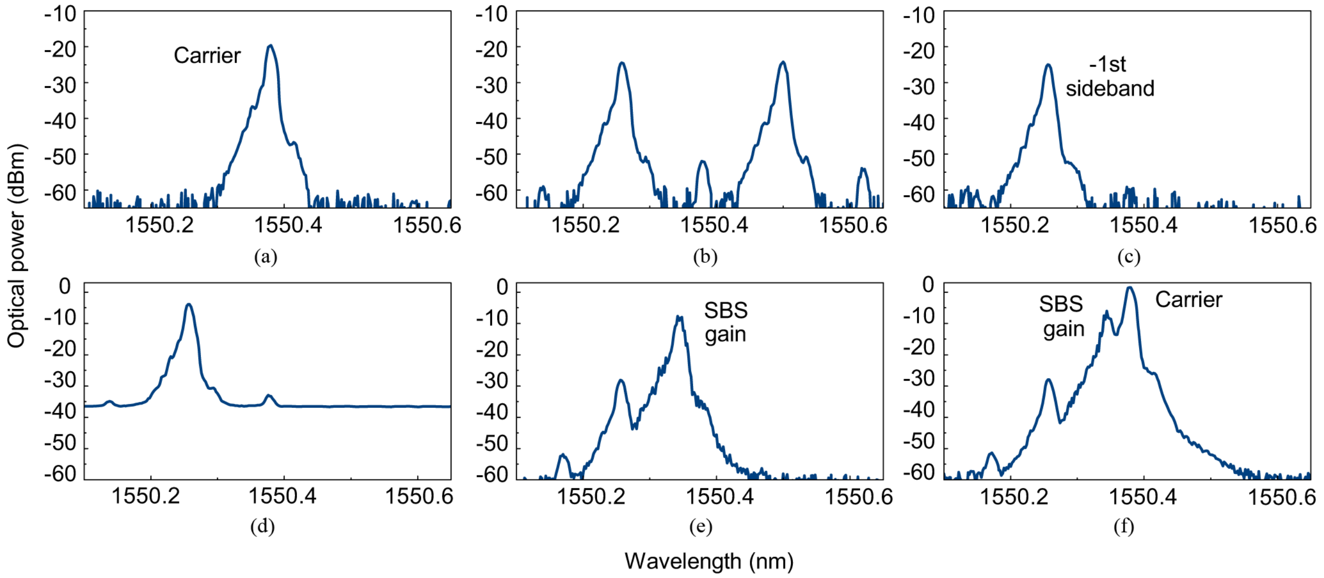


Fig. 5. Measured optical spectra along the experimental setup. (a) Optical carrier at point A. (b) Carrier suppression at point B. (c) Remained −1st sideband after the WaveShaper. (d) −1st sideband amplified by EDFA. (e) SBS gain spectrum without optical carrier. (f) SBS gain spectrum and optical carrier at point E.

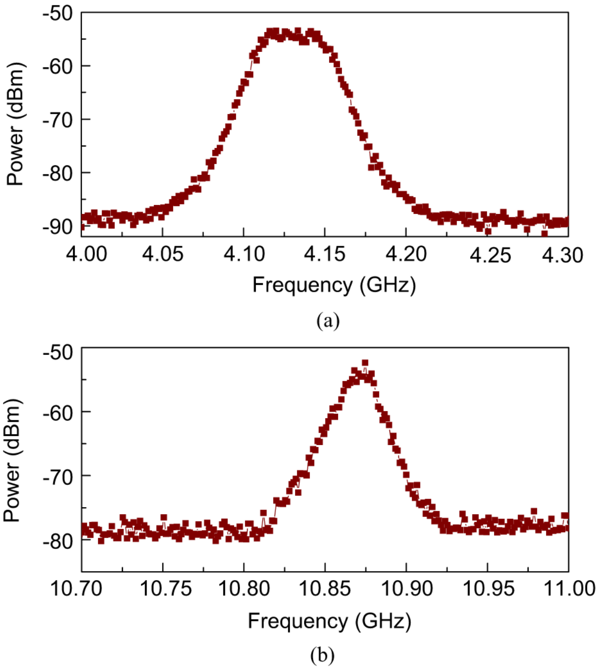


Fig. 6. (a) Measured SBS gain spectrum in the electrical domain with a 3-dB bandwidth of 40 MHz and a 20-dB bandwidth of 87 MHz. (b) Intrinsic SBS gain spectrum without frequency shifting and spectrum shaping having a 3-dB bandwidth of 20 MHz and a 20-dB bandwidth of 91 MHz.

TABLE I
PARAMETER OF THE WDM CHANNELS IN THE CHANNELIZER

Channel	**Carrier Wavelength (nm)**	**Frequency shift (GHz)**
CH-1	1550.375	15.00
CH-2	1551.175	15.08
CH-3	1551.975	15.16
CH-4	1552.775	15.24
CH-5	1553.575	15.32

The wavelength spacing of the WDM channels is 0.8 nm and the increment of the frequency shift is 80 MHz.

The wavelength-shifted lightwaves are then injected into PolM-2, to implement spectrum shaping. In general, from (1), a desired optical power spectrum, $I_p(\omega_p)$, should be formed, as long as the intrinsic SBS gain spectrum, $g_0(\omega_p)$, and the target gain channel, $g(\omega)$, are given. Therefore, a well-designed electrical signal with specific waveform can be generated via the arbitrary waveform generator (AWG) and applied to PolM-2, to obtain the desired optical power spectrum. Here, the spectrum shaping is done by using multiple optical comb lines, which will enable the generation of a narrow and flat-top SBS gain spectrum. In our experiment, an AWG (Tektronix AWG 7102) and a low-frequency and high-power amplifier (Agilent 8447D, 0.1 $\sim$ 1300 MHz) are jointly used to provide the required RF spectrum to drive PolM-2. In detail, two, three, four, or more discrete optical comb lines can be generated by applying electrical signals with frequency components of tens of megahertz to PolM-2. These generated optical comb lines with a uniform or nonuniform power distribution are amplified and then used as the pump sources for different channel characteristics. The pump sources are controlled to exceed the threshold of the SBS effect using an erbium-doped fiber amplifier (EDFA) and then inputted into a 25-km SMF, such that the SBS spectra are observed in each WDM channel in the backward direction.

To clearly show the operation of the system, the desirable optical spectra are shown in the inset of Fig. 4. At points A, B, C, D, and E, the carrier, the carrier suppression, the frequency-shifted lightwave, the spectrum-shaped lightwave, and the combination of the resulting SBS gain and the carrier in each WDM channel are illustrated.

When an RF tone at 15 GHz is applied to PolM-1, two first-order sidebands are generated with the carrier suppressed,

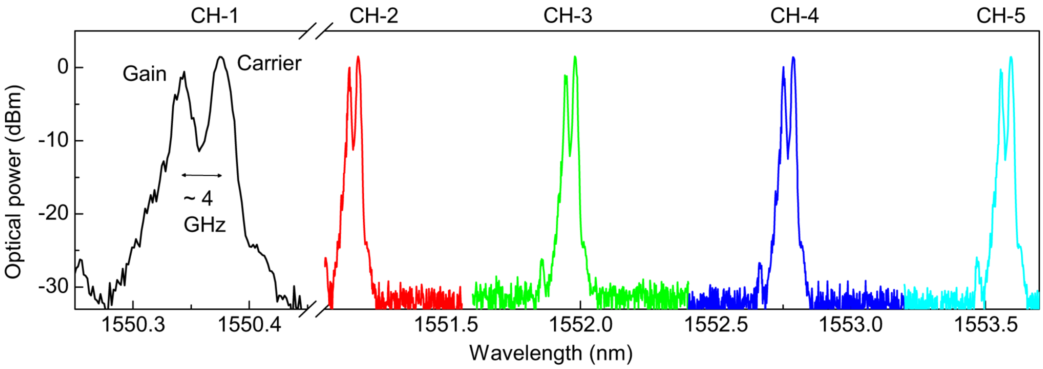


Fig. 7. Measured optical spectra for the WDM channels when a frequency shift of ~ 15 GHz is performed.

as shown in Fig. 5. By filtering out the +1st sideband using the WaveShaper, only the −1st sideband is kept and a 15-GHz frequency shift with respect to the carrier is realized. By pumping the SMF with the amplified −1st sideband, an SBS gain channel, which is about 4 GHz away from the carrier, is achieved, as shown in Fig. 5(e) and (e). These measured optical spectra agree well with the analysis shown in the inset of Fig. 4.

For the spectrum shaping, an RF signal generated by the AWG is applied to PolM-2. Under a carrier-suppressed modulation, an optical comb with two comb lines and a comb spacing of 22.2 MHz is generated, which serves as the pump source. According to (2), an improved channel profile of the spectrum-controlled SBS gain can be achieved by using the designed pump source. To more clearly show the SBS gain profile, a zoom-in view, obtained by beating the optical carrier and the SBS gain spectrum, is shown. From Fig. 6(a), it is clearly seen that the gain spectrum or the gain channel is located at 4.12 GHz with a 3-dB bandwidth of 40 MHz and a 20-dB bandwidth of 87 MHz. Thus, the shape factor is calculated to be about 2. For the purpose of comparison, the intrinsic SBS gain spectrum is shown in Fig. 6(b), where no frequency shifting and no spectrum shaping are implemented. It is seen that the gain spectrum has a 3-dB bandwidth of 20 MHz and a 20-dB bandwidth of 91 MHz at 10.875 GHz. The corresponding shape factor is 4.5, a value much greater than that with spectral shaping. Therefore, a reduced shape factor, which is of greatly importance for a microwave channelizer, is realized via the spectrum-controlled SBS effect.

From a single gain channel to multiple channels of a channelizer, a number of WDM channels with their parameters listed in Table I are employed, where the wavelength spacing is 0.8 nm. By setting the frequency shift in a frequency resolution up to kilohertz via tuning the frequency of the RF tone from the MSG, the frequency offset between the carrier and the SBS gain spectrum can be accurately tuned to locate the position of each channel. Here, an increment of 80 MHz to the frequency shift among the WDM channels is specified, resulting in a channel spacing of 80 MHz of the microwave channelizer.

In the optical domain, the spectra measured at CH-1 ~ CH-5 are illustrated in Fig. 7. In each WDM channel, an SBS gain spectrum and a corresponding carrier are observed. An excellent uniformity is achieved among all the WDM channels. After wavelength de-multiplexing and optical-to-electrical conversion, the generated multiple channels of the channelizer are sequenced in the microwave domain, as shown in Fig. 8. A 3-dB bandwidth of 40 MHz and a channel spacing of 80 MHz are achieved, thus a microwave channelizer covering a frequency range of 400 MHz at 4 GHz is formed. When more channels are implemented in the microwave channelizer, a frequency coverage up to several gigahertz, even 2 ~ 18 GHz could be achieved. For example, a microwave channelizer operating at ~ 5 or ~ 6 GHz can be achieved if a frequency shift to the WDM channels is adjusted to be ~ 16 or ~ 17 GHz

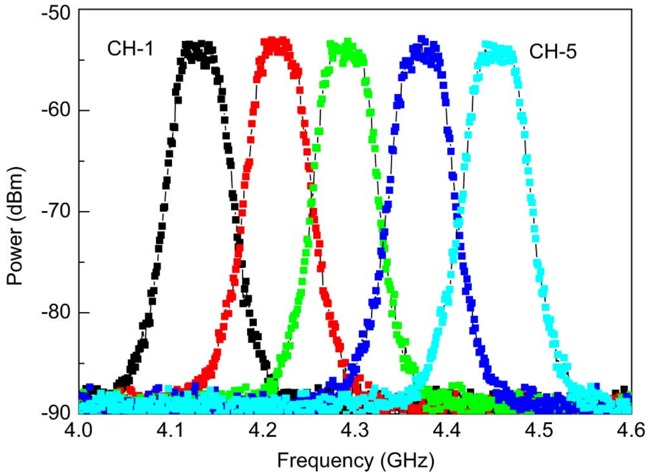


Fig. 8. Microwave channelizer with an operating frequency of ~ 4 GHz (i.e., a frequency shift of ~ 15 GHz to the wavelengths of WDM channels), a 3-dB channel bandwidth of 40 MHz, and a channel spacing of 80 MHz.

From the above experimental results, it is advantageous that both a channel bandwidth of tens of megahertz and a shape factor close to 2 have been achieved in the proposed channelizer, providing high resolution and accuracy for microwave frequency analysis and measurement. With regard to those channelizers in [4] and [7]–[13], a tradeoff between the narrow channel bandwidth and the shape factor was observed since the bandwidth was more than 1 GHz or the shape factor was greater than 4.

B. Tunable Channel Characteristics

Another contribution of the proposed channelizer is the tunable channel characteristics, which will be presented in the fol-

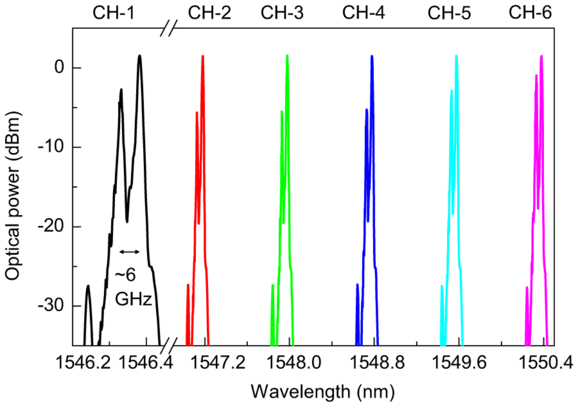


Fig. 9. Measured optical spectra for the WDM channels when a frequency shift of $\sim$ 17 GHz is performed.

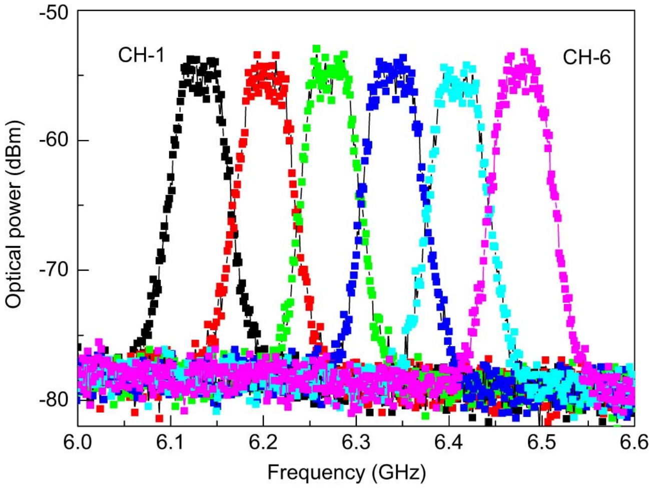


Fig. 10. Microwave channelizer with an operating frequency at $\sim$ 6 GHz (i.e., a frequency shift of $\sim$ 17 GHz to the wavelengths of WDM channels), a 3-dB channel bandwidth of 40 MHz, and a channel spacing of 80 MHz.

lowing. In addition to the improved channel profile, because it is crucial for a microwave channelizer to have tunable channel characteristics for many applications, such as tunable channel spacing, channel bandwidth, and channel profile.

At first, tunable channel spacing of the proposed channelizer is demonstrated. When the increment to the frequency shift among WDM channels is adjusted to be 70 MHz and the frequency shift is tuned to be $\sim$ 17 GHz, a channel spacing of 70 MHz is realized at $\sim$ 6 GHz. From Fig. 9, five WDM channels are established with a wavelength spacing of 0.8 nm. The change in the microwave spacing and in the operating frequency is shown in Fig. 10. It is clearly seen that the microwave channelizer has a different spacing of 70 MHz at the operating frequency of $\sim$ 6 GHz, as well as a 3-dB channel bandwidth of 40 MHz and a channel spacing of 80 MHz. It should be mentioned that the optical power fluctuations within the bandwidth in Fig. 10 are a little greater than 3 dB, compared with that less than 3 dB in Figs. 6(a) and 8, and other follow-up figures. To follow an identical definition of the 3-dB channel bandwidth in this paper, the 3-dB bandwidth is derived from the channel profiles regardless of the fluctuations within the bandwidth in Fig. 10.

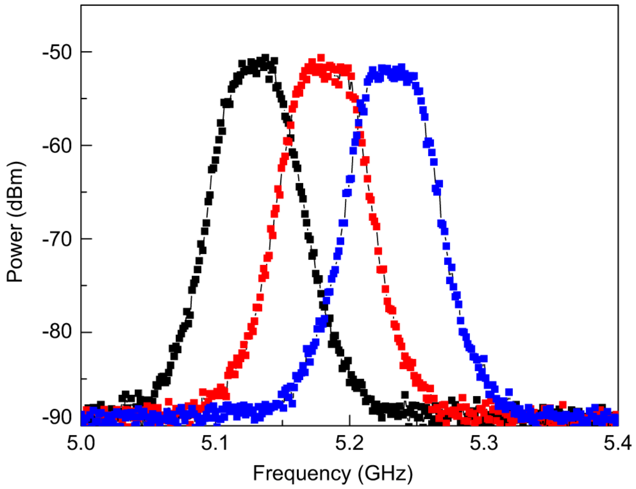


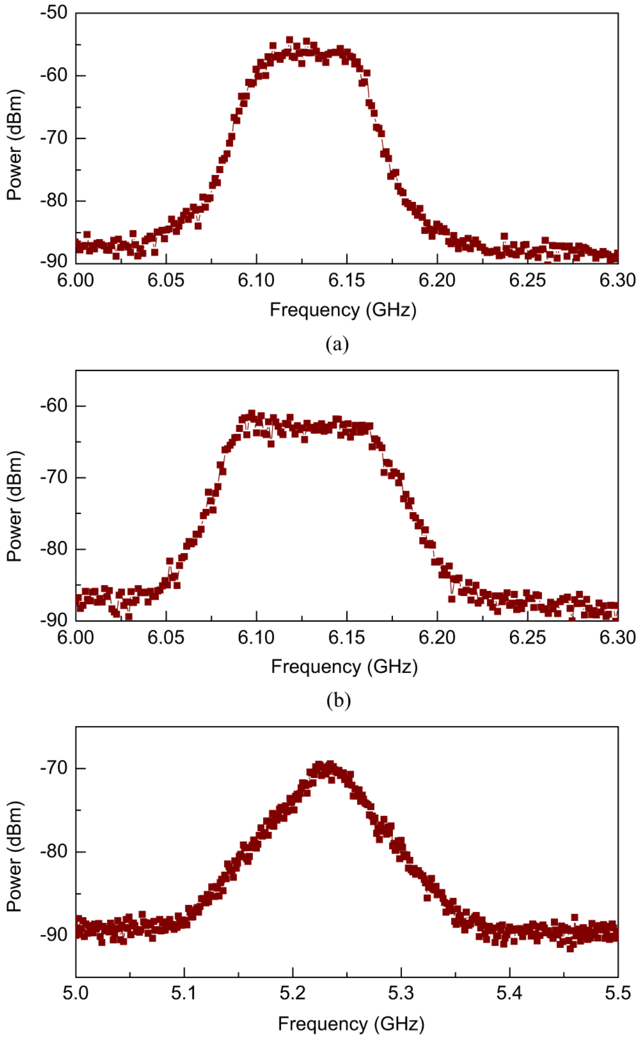
Fig. 11. Microwave channelizer with a channel spacing of 50 MHz at an operating frequency of $\sim$ 5 GHz.

Further, when the increment to the frequency shift is set to be 50 MHz, the resulting channel spacing is reduced to be 50 MHz and the operating frequency is tuned from $\sim$ 6 to $\sim$ 5 GHz, as shown in Fig. 11. Therefore, a tunable channel spacing of 80, 70, or 50 MHz is successfully achieved at different operating frequencies for the microwave channelizer.

The tuning of the channel bandwidth is then experimentally demonstrated. From (2), the channel profile including the channel bandwidth is mostly determined by the spectral shape of the SBS pump source. Thus, tuning the spectral shape of the SBS pump by adjusting the RF signal applied to PolM-2 will result in a tunable bandwidth.

When a sinusoidal signal at 26.3 MHz is applied to PolM-2, three comb lines (i.e., two first sidebands and a residual carrier) are generated. Note that the residual carrier here is kept to flatten the top of the SBS gain because a relative larger comb spacing will induce a concave on the top of the gain spectrum. The resulting SBS gain channel is shown in Fig. 12(a), where the 3-dB bandwidth is increased from 40 to 60 MHz. Further, a composite RF signal generated by the AWG at 10 GS/s is applied to PolM-2, which is expressed as $\sin(2\pi f_1 t + \theta_1) + \sin(2\pi f_2 t + \theta_2)$, where θ_1 and θ_2 are random phase factors, $f_1 = f_2/2 = 13.6$ MHz. Under a carrier suppressed modulation, four comb lines with a comb spacing of 27.2 MHz are formed to generate the SBS gain spectrum. In this case, a channel with a greater bandwidth would be resulted. As shown in Fig. 12(b), an increased 3-dB bandwidth of 90 MHz is achieved in the SBS gain spectrum. It should be pointed out that although the 3-dB bandwidth is broadened to 60 or 90 MHz, a reduced shape factor of 1.7 that is less than 2 is still ensured for the two cases above.

A microwave channelizer with other channel profiles can also be achieved. For instance, a microwave channel with a triangular shape can be generated, as shown in Fig. 12(c), which is achieved by applying an RF waveform with a spectrum corresponding to a triangular shape from the AWG. In fact, microwave channelizers with arbitrary channel profiles can be generated using an RF signal from the AWG for user-defined applications.



(a)

(b)

(c)

Fig. 12. Flat-top microwave channel at an operating frequency $\sim$ 6 GHz with a 3-dB bandwidth of: (a) 60 MHz and (b) 90 MHz; a triangular channel at an operating frequency of $\sim$ 5 GHz.

With regard to the relation among these tunable channel characteristics, the channel spacing and the channel bandwidth can be independently controlled through the spectrum shaping and the frequency shifting, respectively. But the shape factor would suffer small fluctuations during the tuning processing since it is intrinsically determined by the pump power-dependent profile of the SBS gain and the bandwidth of pump source after being spectrum shaped in the convolution operation. For example, as the required channel bandwidth increases, an increased flat top and a reduced power are provide by the pump source owing to the increased bandwidth of the pump source and the fixed saturation power of the EDFA, leading to a reduced shaper factor, as shown in Fig. 12(b).

C. Discussions

In the experiment, the power of the SBS pump source is controlled to exceed the threshold required by the used SBS-active element (e.g., a 25-km SMF). A long SMF or a highly nonlinear fiber can be selected as the element to reduce the threshold. Meanwhile, as the threshold condition is satisfied, the change in the power of the SBS pump source would also impose influences on the channel profile. Thus, the power of the pump source could be adjusted, as an additional tuning parameter, to improve the channel profile, and to tune the channel bandwidth and the channel profile.

On the other hand, limitations on the channel characteristics are analyzed. Firstly, the channel bandwidth is determined by the convolution of the intrinsic SBS gain spectrum and the power spectrum of the pump source, as shown in (1). Consequently, the bandwidth with a large gain of the electrical amplifier connected to the AWG and the modulation performance to the pump laser source during the spectrum shaping would set a limit on the channel bandwidth. For the channel spacing, its accuracy would be limited, especially at low operating frequency in the process of the frequency shift, due to the imperfect CS-SSB modulation at that frequency, which is implemented by using the combination of the carrier-suppressed double-sideband (CS-DSB) modulation to suppress the carrier and the optical bandpass filtering to remove the $+$ 1st sideband. In addition, the shape factor would suffer small fluctuations as the tuning of the channel bandwidth and/or the channel spacing is carried out.

IV. CONCLUSION

A photonic-assisted microwave channelizer based on the spectrum-controlled SBS effect in an SMF with improved channel characteristics was demonstrated. The fundamental concept to improve the channel characteristics is the use of a spectrum-shaped pump source to generate an SBS gain spectrum with improved top flatness and reduced shape factor. Tunable channel spacing and channel bandwidth were realized by controlling the spectrum of the SBS pump via tuning the RF signal applied for the spectrum shaping. A microwave channelizer with a channel bandwidth of 40, 60, or 90 MHz, a channel spacing of 50, 70, or 80 MHz, and a shape factor of less than 2 was demonstrated in the experiment. Tunable channel profiles including the triangular and the flat-top ones also were achieved.

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