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Coherent photonic radio frequency channelization based on dual coherent optical frequency combs and stimulated Brillouin scattering

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Abstract. Coherent photonic radio frequency (RF) channelization based on dual coherent optical frequency combs (OFCs) and stimulated Brillouin scattering (SBS) is proposed and demonstrated. By using the dual OFCs to multicast a wideband RF signal and form a series of SBS gain responses simultaneously, the frequency components of the 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 megahertz), and all the information in the RF signal is retained after the channelization. The channelization fineness can be tuned by adjusting the two OFCs' free spectral ranges. An experiment is carried out. Photonic RF channelization with channel spacing of 80 MHz and a crosstalk suppression of more than 19.52 dB is realized. [DOI: 10.1117/1.OE.55.4.046106]

Keywords: microwave photonics; channelization; optical frequency comb; stimulated Brillouin scattering.

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1 Introduction

Channelizing a broadband signal into a number of frequency channels compatible with current electronics is strongly required in RF receivers working at high frequency and large bandwidth, which are increasingly desired in modern RF systems of radar,[1,2] electronic warfare,[3] and communication satellites.[4,5] Recently, photonic technologies to realize the RF channelization have been widely researched due to the advantages of large bandwidth, high frequency, flat frequency response, good isolation, and immunity to electromagnetic interference.[6–12]

Several photonic-assisted RF channelizer approaches have been proposed and demonstrated.[6–12] In Ref. 6, the RF signal is modulated on an optical carrier and then split into several consecutive ways by using several physically distinct narrowband optical filters. However, this approach has strict requirements with the optical filters, which need to have precise center frequencies and identical and narrow bandwidths. Another approach is to create an array of the RF signal copies by modulating the RF signal on an optical frequency comb (OFC).[7,8] Different frequency components of the RF signal are selected by using a periodic optical filter with a free spectral range (FSR) slightly different from that of the OFC. In this way, the RF signal is effectively split into a number of frequency channels. However, only the identification of the frequency band of the RF signal can be realized, but the information carried by the RF signal is lost.[6–8] A coherent photonic-assisted RF channelizer has been proposed to solve this problem by using a free-space diffraction grating and an OFC.[9] The RF signal is modulated at an optical carrier and then split into several consecutive channels. An OFC is inserted, and each optical comb line has a constant frequency difference to the center frequency of the corresponding channel. For all the channels, every portion of the RF signal is translated to the same intermediate frequency (IF) band after photodetection. In this way, the information carried by the RF signal is fully preserved. However, the wavelength drift of the diffraction grating or the optical microwave signal will affect the system performance. To avoid this problem, coherent channelization using two coherent OFCs and digital in-phase/quadrature (I/Q) demodulation was proposed and demonstrated.[10] Digital signal processing is employed to realize high-frequency resolution and high crosstalk suppression. The approach has a strict requirement of precise phase and amplitude match between I and Q tributaries in each channel. By introducing polarization I/Q demodulation,[11] this strict requirement can be mitigated. Another approach to realize a coherent channelizer is using the stimulated Brillouin scattering (SBS) effect to form the narrowband optical filters.[12] However, in order to create the desired frequency shifts to form the SBS-based filters, a number of microwave sources with designated frequencies are required. Thus, the system would be cumbersome and costly. In addition, the output channelized signals are still in the RF band with different center frequencies, so additional local oscillators (LOs) are needed to perform downconversion.

Recently, we have proposed a novel coherent photonic RF channelizer with high resolution based on dual coherent OFCs and the SBS effect.[13] Two coherent OFCs with different FSRs are used, where copies of the RF signal are created in the optical domain by using the signal OFC, while periodic optical filters are formed based on the SBS effect using the local OFC as the pump. Different frequency components of the RF signal are selected by the SBS-based filters around different comb lines of the signal OFC. A portion of the local

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OFC is reflected and combined with the SBS-amplified signal OFC. After wavelength demultiplexing and photodetection, the RF signal is channelized. The RF information is preserved. The stability of the system is also maintained, due to the same wavelength drifting of the optical RF signal and the filter, which is guaranteed since the two OFCs are generated from the same laser diode (LD). Only two microwave frequencies are needed, and all the channelized RF signals are translated to the same IF band to avoid the additional LOs. The proposed system is relatively compact and cost effective. However, only some preliminary experimental results were reported, which is insufficient to understand the approach.

In this paper, we perform a comprehensive theoretical and experimental study on the photonic-assisted RF channelizer based on dual coherent OFCs and the SBS effect. The system characteristics of working bandwidth, fitness, and flexibility are theoretically and experimentally investigated and analyzed. The influences of the local OFC power with the SBS-based filter response are also investigated to optimize the system performance. An experiment is carried out. Photonic RF channelization of a wideband RF signal composed of a quadrature phase shift keying (QPSK) signal and a single-tone signal is realized. Accurate channel spacing of 80 MHz and a crosstalk suppression of more than 19.52 dB is obtained.

2 Principle

The proposed coherent photonic RF channelization based on dual coherent OFCs and the SBS effect is shown in Fig. 1. Two coherent OFCs with different FSRs are used. The signal OFC has an FSR of δ_{sig}, while the local OFC has an FSR of δ_{lo}. By using a Mach–Zehnder modulator (MZM) biased at the double-sideband carrier-suppressed (DSB-CS) point, the RF signal to be channelized is copied to each line of the signal OFC with the DSB-CS modulation format, as shown in Fig. 1(a). The DSB-CS modulation is used here since it is easier and simpler to realize than the single-sideband carrier-suppressed modulation format. The modulated signal is used as the probe signal and introduced into a length of high-nonlinear fiber (HNLF). On the other path, the local OFC is used as the SBS pump source and injected into the HNLF in a counterpropagating direction through an optical circulator. The SBS gain effect is realized with the modulated RF signal in the HNLF. The signal being amplified by the SBS gain effect and the reflected part of the local OFC are coupled together, as shown in Fig. 1(b). Due to the difference of the two OFCs' FSRs, it can be seen that each comb line of the reflected local OFC carries different frequency components of the RF signal. Such a signal is then demultiplexed; thus, each channel extracts different frequency components of the RF signal, corresponding to one comb line of the local OFC. The demultiplexed optical signal in each channel gets coherent detection in a photodetector (PD) to get the channelized information.

The signal OFC with n comb lines can be expressed as

$$E_{\text{sig}}(t) = E_{\text{sig}} \sum_{k=1}^{n} e^{j2\pi t[f_{\text{sig}}(1)+(k-1)\delta_{\text{sig}}]}, \tag{1}$$

where $f_{\text{sig}}(1)$ is the frequency of the first line and E_{sig} is the magnitude of the comb lines. The RF signal with frequency of f_{RF} is multicast by the signal OFC through DSB-CS modulation; thus, the kth multicast copy will have both upper and lower sidebands of the RF signal, with the frequency being as follows:

$$\begin{cases} f_{\text{lowsig}}(k) = f_{\text{sig}}(1) + (k-1)\delta_{\text{sig}} - f_{\text{RF}}, \\ f_{\text{upsig}}(k) = f_{\text{sig}}(1) + (k-1)\delta_{\text{sig}} + f_{\text{RF}}. \end{cases} \tag{2}$$

Only red- or blueshifted copies will be considered, which is determined by the relative position of the local OFC and the signal OFC. When the frequency of each comb line in the local OFC is higher than that of the corresponding comb line in the signal OFC, only the blueshifted copies of $f_{\text{upsig}}(k)$ need to be considered, since the SBS effect will not gain the redshifted copies. Otherwise, with the frequencies of the local OFC comb lines lower than the corresponding ones of the signal OFC, only the redshifted copies of $f_{\text{lowsig}}(k)$ need to be considered. In the following analyses and experiments, the case of using the blueshifted copies of $f_{\text{upsig}}(k)$ is considered. There is also a requirement with the RF signal to avoid the spectrum aliasing. To satisfy this, $0 < f_{\text{RF}} < \delta_{\text{sig}}/2$ or $\delta_{\text{sig}}/2 < f_{\text{RF}} < \delta_{\text{sig}}$ should always be satisfied. Thus, the

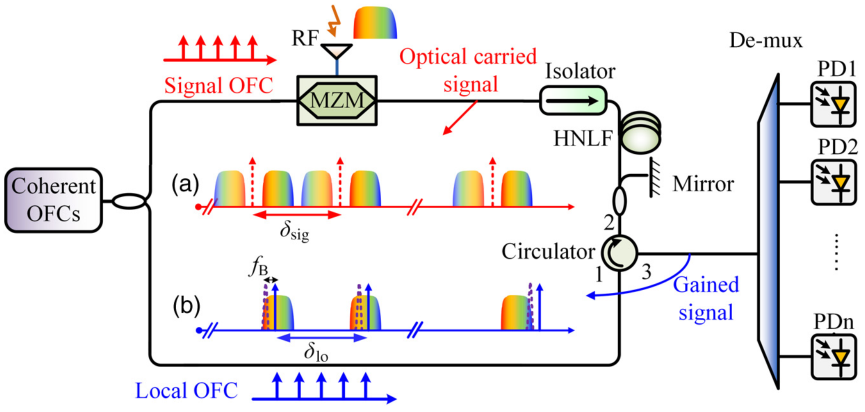

Fig. 1 Schematic of the proposed coherent photonic RF channelization based on SBS and dual coherent OFCs. PC, polarization controller; OFC, optical frequency comb; MZM, Mach–Zehnder modulator; HNLF, high-nonlinear fiber; De-mux, demultiplexer; PD, photodetector.

bandwidth of the RF signal to be channelized is limited to $\delta_{\mathrm{sig}}/2$.

With the local OFC as the Brillouin pump waves, each comb line will amplify the Stokes wave with a frequency downshifted by the Brillouin frequency shift f_{B}.[14] Therefore, the center frequency of the SBS gain response with the kth comb line of the local OFC as the pump wave is $f_{\mathrm{lo}}(k) - f_{\mathrm{B}} = f_{\mathrm{lo}}(1) + (k-1)\delta_{\mathrm{lo}} - f_{\mathrm{B}}$. Only part of the kth multicast copy locating in the range of the corresponding kth SBS gain response will be selected and output at the kth channel. The center frequency of the output RF signal at the kth channel will be

$$f_{\mathrm{RF}}(k) = f_{\mathrm{lo}}(1) - f_{\mathrm{sig}}(1) - f_{\mathrm{B}} + (k-1)\delta_{\mathrm{FSR}}, \tag{3}$$

where δ_{FSR} is the FSR difference of the two OFCs, which is equal to $\delta_{\mathrm{lo}} - \delta_{\mathrm{sig}}$. Considering the profile of the SBS gain response,[15] the intensity of the output optical-carried RF signal in the kth channel is as follows:

$$\begin{aligned} E_{\mathrm{out}}(f_{\mathrm{RF}}, k) \\ = E_0(f_{\mathrm{RF}}, k) \exp\left(\frac{G(\Gamma/2)^2}{\{f_{\mathrm{upsig}}(k) - [f_{\mathrm{lo}}(k) - f_{\mathrm{B}}]\}^2 + (\Gamma/2)^2}\right), \end{aligned} \tag{4}$$

where E_0 is the optical-carried RF signal before being SBS amplified, $f_{\mathrm{lo}}(k)$ is the frequency of the kth comb line of the local OFC, Γ is the full width at half maximum, and G is the exponential SBS gain. The gains of each channel are almost the same, since each line of the local OFC has equal power and similar wavelengths.

Then the SBS gained optical-carried RF signal will be coupled with the kth comb line of the local OFC reflected from the mirror and injected into a PD by the use of an optical de-mux to separate all the channels. In each channel, the corresponding channelized information is output at the center frequency of f_{B}. In this way, the RF signal will be sliced into a number of parallel parts and converted into signals with the same center frequency of f_{B}. Since the signal OFC and local OFC are coherent, no information is lost. Thus, a coherent photonic RF channelizer is realized based on dual coherent OFCs and the SBS effect.

The effect of the frequency difference of the local OFC's comb lines on the center frequency of the SBS gain response in different channels is also analyzed. The Brillouin frequency shift f_{B} can be expressed as[15]

$$v_{\mathrm{B}} = 2nV_{\mathrm{A}}/\lambda_{\mathrm{L}}, \tag{5}$$

where V_{A} is the acoustic velocity, n is the refractive index of the fiber core, and λ_{L} is the wavelength of the pumping light in vacuum. When the local OFC comb lines are near 1550 nm, the difference of f_{B} due to the wavelength difference of the pumping wave is ~6 MHz/nm, which can be ignored when the comb lines of the local OFC are close enough.

3 Experimental Results and Discussions

An experiment is carried out based on the scheme shown in Fig. 1. The dual coherent OFCs are generated from the same LD seed with the setup shown in Fig. 2. The OFCs are generated with five comb lines based on a polarization modulator (PolM).[16] The continuous-wave light at 1550.095 nm (generated by TeraXion PS-NLL) is split to two branches, and a PolM (Versawave, 40 GHz) is used in each branch. The light in the up- and the low-branch is modulated by an RF signal with a frequency of 21.28 and 21.20 GHz to generate OFCs, respectively. To analyze the channelization character of the proposed scheme, a wideband RF signal is generated by combining a 1-Mbps QPSK signal centered at 11.92 GHz generated from Agilent E8267D and a single-tone 12.08-GHz RF signal generated from Anritsu MP1763C. Both the QPSK signal and the single-tone signal have the same power of 10 dBm. The local OFC is amplified by an erbium-doped fiber amplifier and injected into a 1-km HNL dispersion-shifted fiber through a circulator as the pump waves. Part of the local OFC is reflected by a fiber mirror through the circulator and then coupled with the SBS gained signal to serve as local carriers of coherent detection. The de-mux to separate the channels is realized by using a tunable optical filter (Yenista XTM-50). An electrical spectrum analyzer (R&S FSV40, 10 Hz–40 GHz) is used to measure the electrical spectra, and the optical spectra are measured by an optical spectrum analyzer (Yokogawa AQ 6370C). A vector network analyzer (VNA, Agilent N5230A) is used to measure the SBS gain responses.

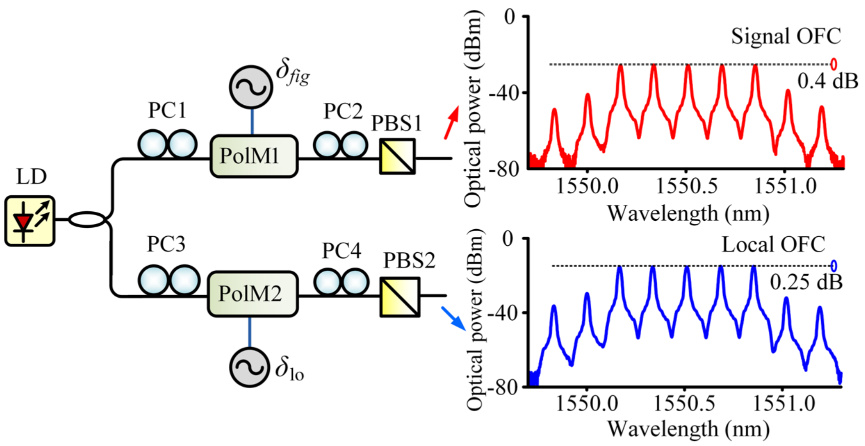

Fig. 2 Experimental setup and the results of the generation of dual coherent OFCs. LD, laser diode; PC, polarization controller; PolM, polarization modulator; PBS, polarization beam splitter.

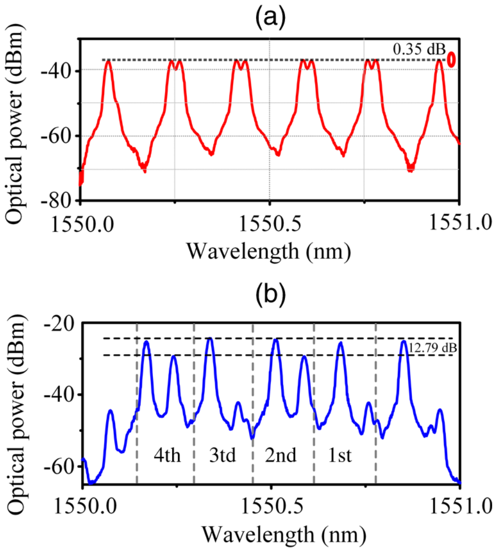

Fig. 3 Measured spectrum of (a) DSB-CS modulated signal OFC and (b) SBS gained signal coupled with the reflected part of local OFC.

The optical spectra of the generated OFCs are shown in Fig. 2. As can be seen, the coherent signal OFC and local OFC with five comb lines are generated, and the FSRs are 21.28 and 21.20 GHz, respectively. The FSR difference of the two OFCs of δ_{FSR} is 80 MHz. The frequency difference of the first lines of the local OFC and signal OFC, $f_{\mathrm{lo}}(1) - f_{\mathrm{sig}}(1)$, is 21.36 GHz. In addition, the OFCs are flat, with the flatness of 0.4 dB for the signal OFC and 0.25 dB for the local OFC. After being DSB-CS modulated by the wideband RF signal combined by a QPSK signal centered at 11.92 GHz and a 12.08 GHz single-tone signal, the optical spectrum of the modulated signal OFC is shown in Fig. 3(a). It can be seen that the RF signal is successfully multicast by the signal OFC through DSB-CS modulation. The flatness of the signal OFC after being modulated is still within 0.35 dB.

The power of each comb line of the amplified local OFC is measured to be ∼9 dBm. With the local OFC comb lines functioning as pumping light, the SBS-amplified optical signal and the reflected part of the local OFC are combined together, with the optical spectra shown in Fig. 3(b). According to Eq. (3), four-channel channelization will be realized when the OFCs have five comb lines. It can be seen that part of the local OFC is successfully reflected as the optical carrier in each channel. In addition, in the second and fourth channels corresponding to the location of the modulated RF signal frequency components, obvious SBS gain selected sidebands can be seen. The selected sidebands are at least 12.79 dB higher than those of the first and third channels where no modulated RF frequency component is located.

Since the SBS gain response determines the channel crosstalk, the relationship of the SBS gain response with the pump power is investigated. The SBS gain responses are measured by a high-resolution optical VNA[17] with the scheme shown in Fig. 4(a). The pump power is controlled by adjusting the attenuator. The SBS gain responses with the pump power tuning from 4 to 15 dBm at a step of 1 dBm are shown in Fig. 4(b). The Brillouin frequency shift f_{B} is 9.19 GHz. It can be seen that the center frequencies of the SBS gain responses are the same. The shape factor, which is the ratio of the 15-dB bandwidth to the 3-dB bandwidth of the SBS gain response, affects the crosstalk among the channels. The improvement of the shape factor will surely depress the crosstalk. As can be seen, the shape factor improves with increasing pump power, with the value decreasing from 4.75 to 1.58 when the pump power increases from 8 to 15 dBm. Since the shape factor is defined as the ratio of the 15-dB bandwidth to the 3-dB bandwidth, and for the cases with pump power lower than 8 dBm, the largest relative gain is lower than 15 dB; thus, the values of the shape factor have not been given. With the increasing of the pump power from 4 to 9 dBm, the 3-dB bandwidth decreases from ∼77 to 19.6 MHz at first. After that, the 3-dB bandwidth increases with the increase of pump power and is ∼29.7 MHz when the pump power is 15 dBm, which is due to the SBS saturation effects.[15] Simultaneously, since a number of comb lines will be injected in the HNLF in our scheme, considering the whole power the system can withstand and the noise introduced by the SBS gain effect, a power of ∼9 dBm for each comb line of the local OFC is used in our experiments, with the detailed SBS gain response shown in Fig. 4(c). In this condition, the 3-dB bandwidth is 21.33 MHz, and the shape factor is 3.4799. Furthermore, the shape factor can be improved by utilizing digital feedback control of the pump spectrum.[18,19] In addition, based on our proposed scheme, all channels can be adjusted simultaneously, which ensures the simplicity and flexibility of the system.

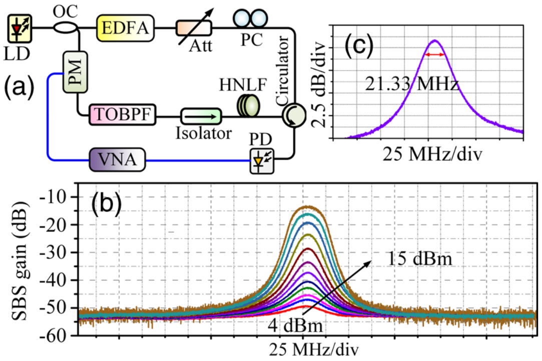

Fig. 4 (a) Measurement setup of the SBS gain responses based on the optical VNA method,[17] (b) measured SBS gain responses with the pump power increasing from 4 to 15 dBm, and (c) the detailed SBS gain response when the pump power is 9 dBm. LD, laser diode; OC, optical coupler; PC, polarization controller; Att, attenuator; PM, phase modulator; TOBPF, tunable optical bandpass filter; HNLF, high-nonlinear fiber; EDFA, erbium-doped fiber amplifier; PD, photodetector. VNA, vector network analyzer.

According to Eq. (3), with the difference of the dual OFCs' first line $f_{\mathrm{lo}}(1) - f_{\mathrm{sig}}(1)$ to be 21.36 GHz, the Brillouin frequency shift f_{B} to be 9.19 GHz, and the FSR difference of δ_{FSR} to be 80 MHz, channelization with four channels will be obtained. The center frequencies of the first to fourth channels are 12.17, 12.09, 12.01, and 11.93 GHz, respectively. In order to demonstrate the multiple frequency channelization performance, a single-tone RF signal at 12.08 GHz and a 1-Mbps QPSK signal centered at 11.92 GHz are coupled together as the input RF signal to be channelized. The measured electrical spectra of each channel within a 500-MHz span are shown in Figs. 5(a)–5(d), respectively. The channelized information corresponding to the

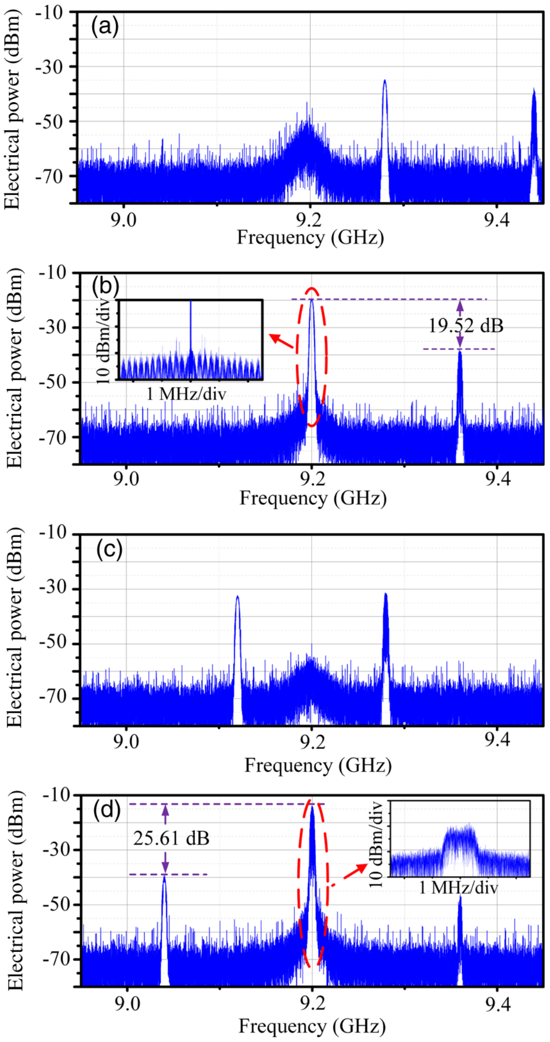

Fig. 5 Measured spectra of (a) first channel, (b) second channel, (c) third channel, and (d) fourth channel, with corresponding channel RF center frequencies of 12.17, 12.09, 12.01, and 11.93 GHz, respectively.

single-tone RF signal and the QPSK signal can be clearly observed in the second and fourth channels, respectively. And the signals are both converted to have the same center frequency of 9.19 GHz. For the two RF signals separated by 160 MHz, the channel crosstalk suppression rates are 19.53 and 25.61 dB within the second and fourth channels, respectively, which is determined by the shape of the SBS gain response. The crosstalk can be further improved by utilizing digital feedback control of the pump spectrum.[18,19] Meanwhile, for the first and third channels, in which no RF component is located, no obvious RF signal component is observed. Thus, channelization with 80 MHz fineness and crosstalk better than 19.53 dB is realized. The spurious frequencies in these spectra are from the amplified noise.[20] The received power in the four channels is compared in Fig. 6, and the channels with RF tones are at least 11.89 dB higher than the ones without RF output tones.

The channelization center frequency corresponding to each channel can be tuned by adjusting the two OFCs' FSRs of δ_{sig} and δ_{lo}. The channel bandwidth is determined by the bandwidth of the SBS-based filter, whose bandwidth and shape factor can be tuned by tuning the pump spectrum. And all channels can be tuned simultaneously for the proposed scheme to ensure simplicity and flexibility. Since the scheme can realize channelization with the RF information being preserved, and good channelization fineness (the bandwidth of the channels), the system may find applications in modern RF systems of radar, electronic warfare, and communication satellites to analyze broadband signals and fit the processing bandwidth of electrical modules. Meanwhile, the main challenge with the scheme is how to extend the channel numbers, which will be further studied in future work.

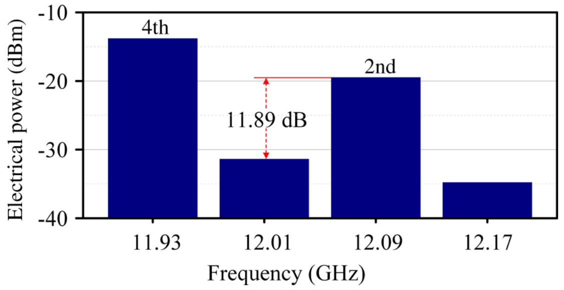

Fig. 6 Received electrical power in the four channels with corresponding channel RF center frequencies of 12.17, 12.09, 12.01, and 11.93 GHz, respectively.

4 Conclusion

Coherent photonic RF channelization with high resolution based on dual coherent OFCs and the SBS effect is proposed and experimentally demonstrated. Channelization of a wideband RF signal composed of a QPSK signal and a single-tone signal with channel spacing of 80 MHz and a crosstalk suppression of more than 19.52 dB is realized. The influences of the local OFC power with the SBS gain responses are investigated to optimize the system performance. The crosstalk can be further improved by utilizing the SBS gain response. The wideband RF signals are channelized and converted into signals with the same center frequency to avoid using additional different LOs to perform downconversion in each channel for subsequent processing. Only two microwave frequencies are required for the entire system to generate the dual coherent OFCs, and no individual tuning is needed in each channel, which makes the system simple and flexible. The system may find applications in modern RF systems of radar, electronic warfare, and communication satellites.

Acknowledgments

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