An Ultra-Wideband Microwave Photonic Channelizer Based on Coherent Optical Frequency Combs and Image-Reject Down-Conversion

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ABSTRACT Radio frequency (RF) channelization receiver is one of the most effective methods for processing ultra-wideband RF signals. In this paper, an ultra-wideband microwave photonic channelizer based on coherent optical frequency combs (OFCs) and image-reject down-converter is proposed and demonstrated. The OFCs used in the system are generated by two dual parallel Mach–Zehnder modulators (DPMZM), and the free spectrum range (FSR) is flexibly adjustable. The image-reject down-converter can not only effectively achieve image separation but also suppress the seven-order distortion and DC offset using balanced detection. A K- and Ka-band RF signal covering the frequency band from 25 to 30 GHz is sliced into 5 sub-channels with 1-GHz bandwidth, two-tone signals with frequencies of 27.5 and 27.51 GHz are used to measure the spurious free dynamic range (SFDR) which is 116.8 dB·Hz$^{2/3}$, the image-rejection is over 66.4 dB, and the error vector magnitude (EVM) is 4.2%.

INDEX TERMS Microwave photonics, channelization, optical frequency comb (OFC), image rejection, balanced detection.

I. INTRODUCTION
As communication and radar detection technology develops, the bandwidth of the radio frequency (RF) signal is increasing rapidly. The broadband multi-service access and communication navigation identification in the civilian field [1], [2], and the frequency-agile radar and electronic warfare systems in the military field, have all put forward the need to manipulate wideband RF signals with the bandwidth of several GHz or even dozens of GHz in the future [3]. Therefore, RF receivers with large instantaneous bandwidth, high resolution, and large dynamic range are required to process multi-band signals arriving at the same time [4]–[7]. There are many effective approaches to realize the reception of ultra-wideband or multi-band signals, one of them is RF channelization receiver [8]. In an RF channelizer, the spectrum of the wideband RF signal is divided into different sub-channels through filter arrays, and then narrowband signals with different center frequencies are obtained in real time, which has a signal acquisition rate of almost 100% [9]. However, traditional channelized receiving technology is limited by the inherent electronic bottlenecks, such as large insertion loss, low dynamic range, serious electromagnetic interference and bulky size [10].

Fortunately, RF channelizers based on microwave photonic technology can solve the above drawbacks. In the last decade, several channelized receiving schemes based on microwave photonics have been reported. Among them, the channelized receiver implemented by spatial optical devices such as optical prisms usually have poor frequency resolution and large power loss [11], which is difficult to meet the development needs of modern electronic systems. As a special
multi-wavelength coherent light source, optical frequency comb has the advantages of wide spectrum range and fixed repetition frequency [12], which is suitable for microwave photonic channelized receiver. In Ref. [9], a scheme based on dual optical combs with FP (Fabry-Perot) cavity filter is proposed, but the FP cavity filter cannot afford to supply the demanding Q factor and wavelength stability. In Ref. [13], a scheme based on a mode-locked laser and a dispersive fiber is proposed, but the generation scheme of dual optical combs is much complicated. Ref. [14] demonstrates a method which can suppress in-band interference greatly, but suffers the problems of second-order intermodulation distortion (IMD2) and DC offset. OFCs are widely used in many channelized receiving schemes, but it is difficult to generate ideal OFCs with a large number of comb lines, high flatness, and unwanted mode suppression ratio (UMSR) [15], [16], [18].

In this paper, a RF channelizer scheme is proposed, which consists of the generation of OFC and image-reject mixing. The OFC used in the scheme is generated by one DPMZM, and the FSR can be flexibly adjusted. A K- and Ka-band RF signal covering 25-30 GHz is sliced into 5 sub-channels with 1 GHz bandwidth. The system is mainly manipulated in the optical domain, which effectively overcomes the electronic bottleneck. The image-reject mixer can realize image separation of two signals in the same IF range [17]. Balanced detection is also applied in the scheme, which not only reduces the bandwidth and sampling rate requirements of the ADC, but also effectively suppresses the IMD2 and DC offset [19], [20], so that the SFDR of the proposed RF channelizer can reach 116.8 dB-Hz$^{2/3}$.

II. PRINCIPLE

As shown in Fig. 1, a continuous-wave (CW) light generated from a laser diode (LD) is launched into two branches by a 50:50 optical coupler and each one can be expressed as $E_{in}(t) = E_0 \exp(j2\pi f_c t)$, where $E_0$ is the amplitude and $f_c$ is the frequency.

In the upper branch, only local oscillator (LO$_1$) signal is applied to drive MZMa and a push–pull configuration of the sub-MZMs is assumed. The LO$_1$ signal can be expressed as $V_{LO1} = V_0 \sin(\omega_{LO1} t)$, where $V_0$ is the amplitude and $\omega_{LO1}$ is the angular frequency. DPMZM1 have three DC bias voltages, which are denoted $V_{1a}$, $V_{1b}$, and $V_{1c}$, respectively. The output optical signal of the DPMZM1 can be expressed as:

$$E_{DPMZM1} = \frac{E_{in}(t)}{2} \left\{ \cos \left( \frac{\pi V_0}{2V_\pi} \sin \left( 2\pi f_{LO1} t + \frac{\pi V_{1a}}{2V_\pi} \right) \right) + \cos \left( \frac{\pi V_{1b}}{2V_\pi} e^{j\frac{\pi V_{1c}}{V_\pi}} \right) \right\} \quad (1)$$

In the equations, $V_\pi$ is the half-wave voltage of the modulator. Optical carrier, first-order and second-order sidebands of the output optical signal can be written as (2-6) after Jacobi–Anger expansion.

$$E_0 = \frac{E_{in}(t)}{2} \left[ \cos AJ_0 (B) + \cos \left( \frac{\pi V_{1h}}{2V_\pi} \right) e^{j\frac{\pi V_{1c}}{V_\pi}} \right] \quad (2)$$

$$E_{+1} = \frac{E_{in}(t)}{2} \sin AJ_1 (B) e^{j(2\pi f_{LO1} t + \frac{\pi}{2})} \quad (3)$$

$$E_{-1} = \frac{E_{in}(t)}{2} \sin AJ_1 (B) e^{j(2\pi f_{LO1} t - \frac{\pi}{2})} \quad (4)$$

$$E_{+2} = \frac{E_{in}(t)}{2} \cos AJ_2 (B) e^{j4\pi f_{LO1} t} \quad (5)$$

$$E_{-2} = \frac{E_{in}(t)}{2} \cos AJ_2 (B) e^{-j4\pi f_{LO1} t} \quad (6)$$

where $A = \pi V_{1a}/2V_\pi$, $B = \pi V_0/2V_\pi$, and $J_n(\cdot)$ represent the $n$th-order Bessel function. The five lines of OFC are optical carrier, first-order and second-order sidebands, whose amplitude are closely related to the flatness of the five comb

FIGURE 1. Schematic diagram of proposed microwave photonic channelizer. LD: laser diode; DPMZM: dual parallel Mach–Zehnder modulator; LO: local oscillator; EDFa: erbium-doped fiber amplifier; IM: intensity modulator; OBPF: optical bandpass filter; MZM: Mach-Zehnder modulator; PC: polarization controller; PBS: polarization beam splitter; OHC: optical hybrid coupler; BPD: balanced photodiode; EHC: electrical hybrid coupler; EBPF: electrical bandpass filter.
After deformation, \( V_{ld} \) and \( V_{lc} \) can be written as:

\[
V_{ld} = \frac{2V_\pi}{\pi} \arctan \left[ J_2 (B) / J_1 (B) \right]
\]

(9)

\[
V_{lc} = (2N + 1) \ \text{V},
\]

(10)

\[
V_{lb} = \frac{2V_\pi}{\pi} \left[ \pm \arccos \left[ \sin AJ_1 (B) + \cos AJ_0 (B) \right] \right]
\]

(11)

From (9)–(11), when the half-wave voltage of the MZM is 3.5 V and the modulation index (MI) is 0.83, the three DC bias voltages of DPMZM1 \( (V_{ld}, V_{lb} \text{ and } V_{lc}) \) can be calculated as 3.15 V, −6.23 V, and 0 V, under the above condition, a five-line flat OFC can be generated.

If the values of \( V_{ld}, V_{lb}, \text{ and } V_{lc} \) can be properly set in this OFC generation scheme, a seven-line flat OFC can also be generated. The output from DPMZM1 is expressed as the following equations:

\[
E_{DPMZM1} = \frac{E_{in}}{2} \left[ \cos AJ_0 (B) + e^{\frac{j\pi V_{lb}}{2V_\pi}} \cos AJ_1 (B) + e^{\frac{j\pi V_{lb}}{2V_\pi}} \cos AJ_3 (B) \right]
\]

(12)

When the seven optical comb lines representing optical carrier, first-order, second-order sidebands and third-order sidebands have the same amplitude (as 13) shows:

\[
\frac{E_{in}}{2} \sin AJ_1 (B) = \frac{E_{in}}{2} \cos AJ_2 (B)
\]

(13)

It can be easily calculated that \( V_0 = 1.94V_\pi, V_1 = 0.63V_\pi, V_2 = 0.724V_\pi \) and \( V_3 = V_\pi \).

In this scheme, two five lines combs are used and denoted as signal OFC and local OFC, respectively. In the signal OFC, the frequency of each line can be written as:

\[
E_{sig} = \sum_{n=1} B_n \exp \left[ j2\pi \left( f_{sig} (1) + (n - 1)\delta_1 \right) \right] t
\]

(14)

A\(_n\) represents the amplitude of the \( n^{th} \)-order comb line, \( f_{sig} (1) \) represent the frequency of the first comb line and \( \delta_1 \) represent the FSR of signal OFC. Being amplified by erbium-doped fiber amplifier (EDFA\(_1\)), the signal OFC is modulated by a wideband RF signal via a DPMZM3. DPMZM3 works under carrier suppressed single sideband (CS-SSB) condition, and \( \beta \) is the MI. The positive first-order sideband modulated by the RF signal can be written as:

\[
f_{sig - mod} (t) = \beta \sum_{n=1} A_n \exp \left[ j2\pi \left( f_{sig} (1) + (n - 1)\delta_1 \right) \right] t
\]

(15)

In the lower branch, in order to make the local OFC and the signal OFC down-converted to the common IF, the frequency of optical carrier needs to be shifted via an optical frequency shifter (OFS). The OFS consists of intensity modulator (IM) and an optical bandpass filter (OBPF), in which the carrier is first modulated by a tone-signal with a frequency of \( \delta_1 \) and then the positive first-order sideband is selected and launches into DPMZM2. The optical frequency comb generation principle in DPMZM2 is the same as that in DPMZM1. The frequency of each line in this local OFC can be expressed as:

\[
f_{LO} = \sum_{n=1} B_n \exp \left[ j2\pi \left( f_{LO} (1) + (n - 1)\delta_2 \right) \right] t
\]

(16)

where \( B_n \) is the amplitude of the \( n^{th} \)-order comb line, \( f_{LO} (1) \) is the frequency of the first comb line and \( \delta_2 \) is the FSR of the local OFC, \( f_{center}^{n} \) is the center frequency of \( n^{th} \) channel and can be expressed as:

\[
f_{center}^{n} = f_{LO} (1) + (n - 1)\delta_2 = f_{sig} (1) + (n - 1)\delta_1
\]

(17)

As can be seen clearly that \( f_{center}^{n} \) is closely related to both the order of the comb lines and the FSR of signal OFC and local OFC frequency, and the generation of OFC proposed in this scheme is flexibly adjustable.

In order to split the RF modulated OFC and the local OFC into different channels, the signals from the upper branch and the lower branch are sent to respective waveshapers, as is shown from the dashed lines in Fig. 2 (a) and (b).

Each channel contains a modulated RF sideband from the upper branch and a frequency-shifted LO comb line from the lower branch. These two signals are launched into an optical hybrid coupler (OHC) to achieve image-reject mixing. The optical signals output from the OHC can be written as:

\[
E_1 (t) = \left\{ \beta \sum_{n=1} A_n \exp \left[ j2\pi \left( f_{sig} (1) + (n - 1)\delta_1 \right) \right] t + f_{RF} (t) \right\} \cos \alpha
\]

(18)

\[
E_2 (t) = \left\{ \beta \sum_{n=1} A_n \exp \left[ j2\pi \left( f_{sig} (1) + (n - 1)\delta_1 \right) \right] t + f_{RF} (t) \right\} \sin \alpha
\]

(19)
After the balanced photodiode (BPD), a pair of in-phase and quadrature frequency down-converted signals can be obtained.

\[ i_I(t) \propto A_n B_n \cos \left( 2\pi \left[ f_{RF}(t) - f_{center}^n \right] t \right) \] (20)

\[ i_Q(t) \propto A_n B_n \sin \left( 2\pi \left[ f_{RF}(t) - f_{center}^n \right] t \right) \] (21)

Each channel contains a modulated RF sideband from the upper branch and a frequency-shifted LO comb line from the lower branch. These two signals are launched into an optical hybrid coupler (OHC) to achieve image-reject mixing. The optical signals output from the OHC can be written as:

\[
E_1(t) = \left\{ \begin{array}{l}
\beta \sum_{n=1} A_n \exp \left\{ j2\pi \left[ f_{sig}(1) + (n-1)\delta_1 \right] t + f_{RF}(t) \right\} \cos \alpha \\
+j \sum_{n=1} B_n \exp \left\{ j2\pi \left[ f_{LO}(1) + (n-1)\delta_2 \right] t \right\} \sin \alpha \exp(j\phi) 
\end{array} \right. 
\] (22)

\[
E_2(t) = \left\{ \begin{array}{l}
\beta \sum_{n=1} A_n \exp \left\{ j2\pi \left[ f_{sig}(1) + (n-1)\delta_1 \right] t + f_{RF}(t) \right\} \sin \alpha \\
-j \sum_{n=1} B_n \exp \left\{ j2\pi \left[ f_{LO}(1) + (n-1)\delta_2 \right] t \right\} \cos \alpha \exp (j\phi) 
\end{array} \right. 
\] (23)

After the balanced photodiode (BPD), a pair of in-phase and quadrature frequency down-converted signals can be obtained.

\[ i_I(t) \propto A_n B_n \cos \left( 2\pi \left[ f_{RF}(t) - f_{center}^n \right] t \right) \] (24)

\[ i_Q(t) \propto A_n B_n \sin \left( 2\pi \left[ f_{RF}(t) - f_{center}^n \right] t \right) \] (25)

As \( f_{center}^n \) is different in each channel, the modulated RF signals in different channels would be down-converted to the common IF band. Through Fig. 2(c–d), it can be easily found that the IF signal after down-conversion leads to a strong in-band image interference which can be hardly eliminated by electrical filters. In order to effectively suppress the image interference, an electrical hybrid coupler (EHC) is employed, which can easily separate the desired IF signal and the undesired image signal from the common IF band. The electrical spectra after image suppression are shown in Fig. 2(e). Finally, an electrical bandpass filter (EBPF) is used to filter out the desired corresponding IF signal in each sub-channel.

**FIGURE 2.** The schematic diagram of the proposed scheme.

**FIGURE 3.** The optical frequency comb: (a) five lines; (b) seven lines.
III. EXPERIMENT AND RESULTS

An experiment based on the configuration shown in Fig. 1 is carried out. A continuous light wave with a frequency of 193.515 THz and average power of 16 dBm is generated by an LD (Conquer, KG-DFB-40-C36). The optical carrier is equally divided into two parts by optical couple (OC). In the upper branch, a DPMZM1 (Fujitsu FTM7961EX, $V_{\pi}$ is 3.5V) is driven by a 40 GHz single-tone signal to generate signal OFC with the FSR of 40 GHz. The single-tone signal is generated by an analog signal generator (Agilent E8257D). The signal OFC is modulated by a wideband RF signal generated by a vector signal source (Agilent, E8267C) in DPMZM3 (Fujitsu FTM7961EX, $V_{\pi}$ is 3.5 V).

In the lower branch, the optical carrier first uses an IM (Fujitsu FTM7937EZ, $V_{\pi}$ is 3.5 V) and an OBPF (Yenista XTM-50) to achieve frequency shift and then sent to DPMZM2 (Fujitsu FTM7961EX, $V_{\pi}$ is 3.5 V) to generate local OFC. The comb lines of the two OFCs are correspondingly separated by two parallel waveshapers (Finisar 16000S) and sent to the OHC (Kylia COH24) respectively. The output signals from OHC are sent to two BPDs (Finisar, BPDV2150R) to detect the electrical signals.

Fig. 3 shows the five lines and seven lines OFCs. It can be seen clearly that the higher-order sidebands are suppressed by more than 28.4 dB and 20.8 dB respectively, and the unflatness are 1.2 dB and 3.7 dB respectively. However, the increase in the number of optical combs will lead to the increase of modulation index and then the decrease in UMSR.

A two-tone signals testing is used to prove the optimization effect of balanced detection in the system. The frequencies of the two signals are 27.5 GHz and 27.51 GHz, with the powers of 0 dBm for down-conversion. The optical LO with the relative frequency of 27 GHz. The test result is shown in Fig. 4, the fundamental items (500 and 510 MHz) and IMD3 terms (490 and 520 MHz) both have 6-dB improvement after balanced detection. Meanwhile, the IMD2 is significantly suppressed by 64.4 dB, from $-29.8$ dBm to $-94.2$ dBm.

Both the SFDR with and without balanced detection are measured with the two-tone signals. Fig. 5(a) shows the result without balanced detection, and it can be easily calculated that the conversion gain is -12.2 dB and the noise figure (NF) is 14.1 dB. Although the SFDR3 reaches 115.1 dB · Hz$^{1/2}$, the IMD2 is the dominant distortion and drags the SFDR2 to only 85.1 dB · Hz$^{1/2}$, which determines the overall SFDR of the system. Fig. 5(b) shows the result with balanced detection, where the conversion gain is -6.2 dB. The fundamental and IMD3 terms have a 6 dB increase in amplitude after balanced detection, which agrees with the theoretical expectation. Since the simulation is under ideal conditions, the IMD2 is completely suppressed below the noise floor after balanced detection, so it is not drawn in Fig. 5(b).
Since the proposed scheme is to achieve the common IF reception of ultra-wideband signals, the RF signals in different channels will be image interferences to each other after being down-converted to IF domain. The EHC after I/Q down-conversion can effectively achieve image rejection [21], [22]. Due to the lack of an ultra-wideband RF signal source, the 25-30 GHz wideband signal cannot be generated. Therefore, a wideband signal with a center frequency of 25.5 GHz (in channel 1) and a bandwidth of 30 MHz is used as the desired signal, another wideband signal with a center frequency of 28.5 GHz (in channel 4) and a bandwidth of 10 MHz is used as the image interference signal.

The results of image rejection test are shown in Fig. (6). Fig. 6(a) shows that the signals after down-conversion are in the same IF range (1–2 GHz) and the IF signals in channel 1 and channel 4 are image interferences for each other. Fig. 6(b) shows that the IF signal in channel 4 is well suppressed as an image signal, and the suppression effect is deteriorated because of the amplitude and phase imbalance in the EHC. Unlike image interferences, the crosstalk is mainly caused by the residual optical carrier and sidebands. In order to distinguish the influence of other sub-channels on channel 1, we used five single-tone signals with different center frequencies to down-convert to the same IF range from 1.5 GHz to 1.55 GHz and the result is shown in Fig. 7. We can clearly find the channel isolations are all over 22 dB, and 24.1 dB is the image rejection of channel 1 to channel 4.

**FIGURE 6.** Image rejection test: (a) without image rejection; (c) with image rejection.

**FIGURE 7.** Measured channel crosstalk influence of other sub-channels on channel 1.

**FIGURE 8.** Measured EVM and constellation diagram.

Fig. 8 shows the changes in the EVM curves and constellation diagrams with the increase of input power of the RF signal. It is clear that when the RF power ranges from −15 dBm to 10 dBm, the EVM decreases rapidly at first until reaching the bottom at about 4.2%, which is the optimum point of the input RF power. After the optimum point, the IMD3 increases significantly, which deteriorates the constellation diagrams and thus the EVM begins to increase. With the RF power from −10 dBm to 7 dBm, the EVM is below 10%, indicating a large dynamic range of the system.

**IV. CONCLUSION**

A wideband microwave photonic channelization receiver based on dual OFC is proposed and demonstrated by experiment in this paper. The OFC generated by a DPMZM has high flatness and the FSR is flexibly adjustable. An ultra-wideband RF signal can be sliced into 5 sub-channels with 1 GHz bandwidth. It is worth mentioning that the balanced detected image-reject mixer not only suppresses the image interference, but also suppresses the IMD2 and DC offset, which can effectively improve the dynamic range of the system to 116.8 dB Hz$^{2/3}$. The proposed photonic microwave channelizer may have great application prospect in the future electronic warfare, radar system and satellite communication fields.
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