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Frequency comb distillation enabling broadband microwave photonic channelized receiver

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***Abstract*—Microwave photonics channelization has become a promising technology for ultra-wideband RF spectral analysis. In this paper, a wideband microwave photonics channelization scheme based on dual optical frequency combs with comb distillation technique is proposed. A 10 GHz bandwidth RF signal with frequencies from 2 to 12 GHz is down-converted to the same IF band with 1-GHz instantaneous bandwidth, where the in-band crosstalk suppression is larger than 33 dB for all channels, and the spurious-free dynamic range of the system can reach 101.3 dB·Hz$^{2/3}$. Moreover, BERs for all channels without and with distillation are compared.**

Keywords—microwave photonics, optical frequency comb, channelization, distillation

I. Introduction

With the increasing requirement on the frequency and bandwidth in radio frequency (RF) systems. Traditional electronic broadband analog techniques have the drawbacks of limit bandwidth and intrinsic electromagnetic immunity. In contrast to electronic front-ends, microwave photonic techniques due to its unique characteristics and advantages such as small footprint, low loss (0.2 dB/km while RF with 2 dB/m), large bandwidth (i.e., 200 fold wider than the RF spectrum), low nonlinear distortion have attracted great interest by many scholars and industries. Therefore, microwave photonics designs provide freedom to frequency translate ultra-wideband signals, allowing receiver designs to accommodate broad bandwidth and frequency reconfigurable. In recent years, microwave photonics have been widely used for broadband signal channelization.

Many microwave photonics broadband signal channelization approaches have been reported [1-6]. In [1], an microwave photonic channelizer based on polarization multiplexing and the photonic dual-output image reject mixing was presented. An RF signal with 9.6-GHz bandwidth centered at 14 GHz is divided into 8 channels with 1.2-GHz bandwidth, while the image reject ratio (IRR) performance of the dual output microwave photonic image reject mixing is low to 21 dB. In [2], Z. Tang et al. provided a coherent optical RF channelizer with broad instantaneous bandwidth and large in-band interference suppression, where a Ku-band RF signal with an instantaneous bandwidth of 5 GHz is sliced into five consecutive sub-channels with 1-GHz instantaneous bandwidth with IRR about 25 dB. In [3], W. Zhai et al. proposed an ultra-efficient broadband photonic channelizer based on polarization-division multiplexing and integrated dual-polarization coherent detection receiver, a 2-14-GHz signal is divided into 12 channels with 1-GHz sub-channel bandwidth, with the IRR is greater than 34 dB over 1-GHz bandwidth and the SFDR is around 94.2–97 dB•Hz$^{2/3}$. In[4], X. Xu reported a broadband RF channelizer with up to 92 channels using a coherent microcomb source, which achieved RF slicing resolution of 121.4 MHz by the high-Q passive microring resonator（MRR）.

In all, massive of microwave photonics broadband signal channelization schemes are proposed, and the number of channels and the covered RF band are varied. The dual optical frequency combs have been effectively demonstrated as a channelizer for RF signal processing, which allows for broadband frequency signals processed by multiple low speed receivers in parallel, reducing the receiver sub-components bandwidth requirements such as filters, analog-to-digital converters, and digital signal processors (DSP). While the optical frequency combs sources can be generated by electro-optic (modulator based) combs [7], integrated mode locked lasers [8], parametric combs [9], and micro-resonators [10]. Electro-optic combs offer the flexibility of optical linewidth, optical carrier-to-noise ratio, high optical power per comb line, and tuning the frequency spacing. Although the numerous dual frequency comb microwave photonics broadband channelization have been demonstrated, the limited discussion of these channelization approaches performance, such as the effect of the modulator nonlinearity and the broadband noise. In this paper, we propose a wideband microwave photonics channelization based on dual optical frequency combs with combs distillation technique. We conduct detailed investigations on the RF photonic front-end performance with reducing the broadband noise and modulator nonlinearity by the combs distillation technique.

II. OperationPrinciple

Fig. 1 shows the schematic diagram of the proposed frequency comb distillation enabling broadband microwave photonic channelized receiver. An optical carrier is generated by a laser source and split into two branches by a 50/50 optical coupler (OC). In the upper branch, the optical carrier is deeply modulated by the Mach-Zehnder modulator (MZM) which is driven by a RF signal with the frequency of $F_{RF,}$ and then subsequent to phase modulator (PM) driven by a RF signal with the frequency of $2*F_{RF}$.

Then the generated optical frequency comb (OFC) is fed into an MZM which is worked at the double sideband suppressed-carrier (DSB-SC) modulation mode and driven by a received wide-band RF signal. In the lower branch, a RF signal with frequency of F_{rf1} is fed into an MZM which is biased at its null-point to linearly modulate the light from the optical carrier. After being amplified by an EDFA, the upper side band signal with frequency of f_C+f_{RF} is selected by a wideband optical band-pass filter OBPF, then the up-shifted optical carrier is fed into the MZM which is work at the DSB-SC modulation mode and drive by a RF with the frequency at

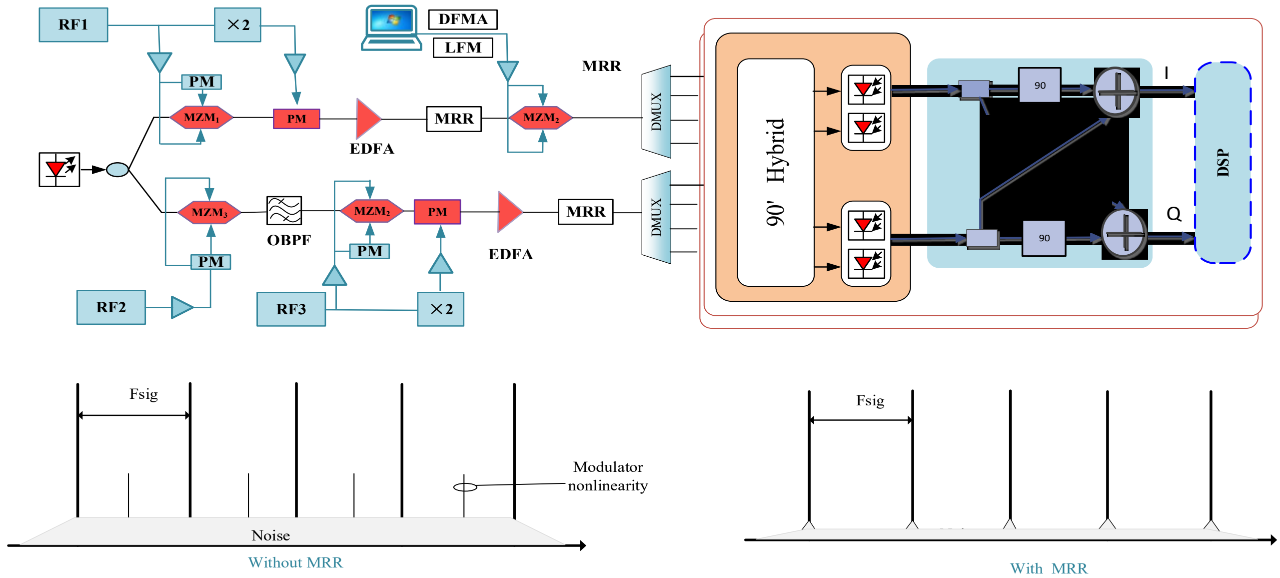


Fig. 1. Schematic diagram of the proposed frequency comb distillation enabling broadband microwave photonic channelized receiver.

F_{rf2}. Then sent into a PM which driven by the RF3 with x2 frequency multiplier. After that an Erbium-doped fiber amplifier (EDFA) is used to amplify the electro-optic effect based OFC. However, the optical broadband noise stemming from amplified spontaneous emission (ASE) and the nonlinearity noise due to the harmonic distortion will contaminate the amplified comb line, thus a high Q factor MRR with a narrowband bandwidth is used to filter the OFC, after passing through the MRR the broadband noise and the harmonic distortion are rejected. Then the output signals of the wavelength division multiplexers (Dmux) are sent into the signal port and the LO port of a 90° optical hybrid, respectively. At the output of the optical hybrid, two quadrature and in-phase output signals are respectively detected by the two balanced photodetectors (BPDs).

Then two photocurrents go through an electrical quadrature hybrid (EQH) to separate the I/Q RF signals. And the derived I/Q RF signals are injected into two band-pass filters (BPFs) for filtering out the interference signals. Thus the frequency components located at the left and right sides of the photonic LO are down-converted to the same IF， and the narrowband RF signal can be further processed in the DSP.

III. SETUP

A proof-of-concept system is implemented to verify the performance of the proposed frequency comb distillation enabling broadband microwave photonic channelized receiver, where the key simulation parameters are summarized in Table 1. The simulation is conducted by using VPItransmissionMaker11.4 and Matlab. At the transmitter side, both a wideband linear frequency modulated (LFM) RF signal with a center frequency of 7 GHz and a bandwidth of 10 GHz covering 2-12 GHz for easing test the channelize process and a multi-band digital orthogonal filtering (DOF) [11] signal covering 2-12GHz are generated for detailed analysis of the performance using Matlab. After that, a continuous light wave with the center frequency of 193.1 THz, linewidth of 10 MHz and the output power of 17 dBm is split into two equal parts by an optical coupler. In the upper branch, the optical carrier is used to seed two electro-optic frequency comb generators based on cascaded MZM and PM, The driving signals of the electro-optic modulator are generated from a single-tone RF signal with the frequency of 13GHz and doubled to create two driving signals of frequency 25 GHz, Due to the lines of the OFC effect by the strength of the driving signal where the RF power amplifiers are used to boost the RF power to ensure that the power of driving microwave applied is suitable. The MZM_1 with a half-wave voltage of 3.5V and an insertion loss of 6 dB is worked at the minimum transmission point (MITP) . The other path is first modulated by the MZM_3 biased at its null-point and driven by RF_2 with a frequency of 7.5 GHz, An optical band-pass filter with the bandwith of 10 GHz is used to select the 1^{st} optically carried RF sidebands and the selected optical carrier is modulated by the cascaded MZM and PM to generated local OFC, which is same as the upper branch and the driving signal driven by another microwave RF_3 with frequency of 12.5GHz. Then a relatively wideband OFC are generated with a few control parameters and the comb spacing is twice the drive frequency of the RF signal generator. The generated Lo-OFC and Sig-OFC with the comb spacing of 25 GHz and 26 GHz. The generated Sig-OFC and Lo-OFC are then amplified by EDFA to achieve a relatively high power, respectively, where the EDFA has a noise figure of 4dB and Gmax = 25dB. And then the amplified Sig-OFC and Lo-OFC are sent to the gaussian comb_I type filter act as the MRR with the FSR of 26 GHz and 25 GHz to suppress the nonlinear and the wideband optical noise. Subsequently, the distillation Sig-OFC goes through a MZM biased at its null-point to linearly modulate the under test RF signal, thus the RF signal is up-converted to optical frequency and copied by the Sig-OFC, then separated by Demux and sent to the signal port of the optical hybrid. And the separated distillation Lo-OFC by another Demux are sent to the LO port of the optical hybrid. Then detected by BPDs with 40-GHz bandwidth of and 0.8-A/W responsivity. The outputs of BPDs are processed by an electrical quadrature hybrid (EQH) to address the spectrum-aliasing problem, and then two I signals and Q signals are obtained, and a lowpass filter (LPF) with the band-with of 2GHz is utilized to rejected the out-of-band frequency components. Then, the received electrical signals are further processed via Matlab.

Table 1 Parameters

Parameter	Value
Sig-OFC	26 GHz
Lo-OFC	25 GHz
ECL center frequency	193.1 THz
Laser linewidth	10 MHz
RF1	13 GHz
RF2	7.5 GHz
RF3	12.5 GHz
Noise figure of EDFA	4 dB
MZM insertion loss	6dB
Number of channels, N	10
LPF bandwidth	1 GHz
Photodiode responsivity	0.8 A/W
90◦EH	3◦phase imbalance

IV. RESULTS AND DISCUSSIONS

The generated Lo-OFC and Sig-OFC with the comb spacing of 25 GHz and 26 GHz after amplification are shown in Fig. 2(a), the blue solid line and red dashed line represent the Lo-OFC and Sig-OFC, respectively. Due to the limited extinction ratio of the MZM, the Lo-OFC and Sig-OFC are not high-purity, the distortions are not completely separated, which will affect the performance of the channelization. Meanwhile, the flatness of comb is relatively poor (about 2dB). Fig. 2(b) stands for the comb after passing through the MRR. We can see that the broadband noise and the harmonic distortion are alleviated, due to the accurately design the FSR of the MRR to match the line spacing of the micro-comb.

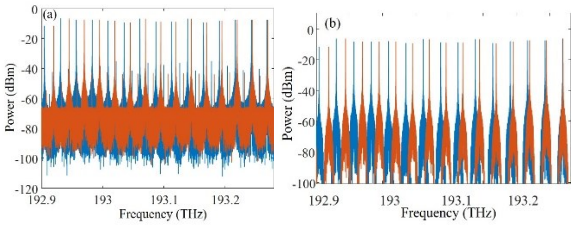


Fig. 2. Spectra of (a) Lo-OFC and Sig-OFC without distillation and (b) Lo-OFC and Sig-OFC with distillation.

The corresponding waveforms of the channelized output IF signals at 0-1 GHz in each channel are shown in Figs. 3(a)-(j), as can be see that the broadband RF signal with 10-GHz bandwidth and 7-GHz center frequency has been divided into ten narrowband RF signals with 1-GHz bandwidth. The corresponding output electrical spectra of the down-converted IF signal of channel-1 and channel-10 are also shown in the Figs. 3(I) and (II), the out-of-band crosstalk rejection of channel-1 and channel-10 are large than 35 dB and 33 dB, respectively.

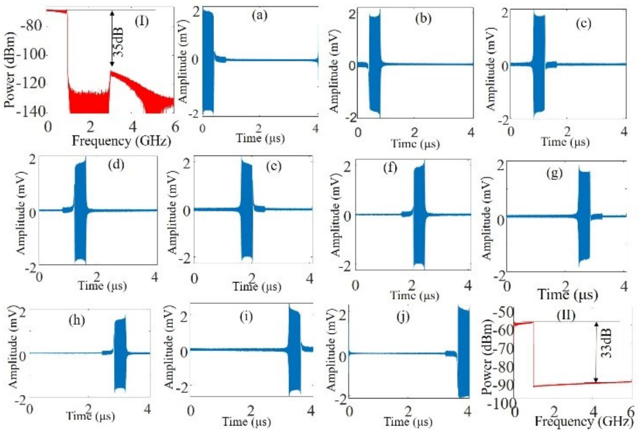


Fig. 3. Output 0–1 GHz IF signal waveform at the (a)-(j) Ch-1 to Ch-10

Then, the spurious-free dynamic range (SFDR) of the proposed microwave photonic channelization with and without distillation is measured. Taking channel 10 as an example, a two-tone RF signal with frequencies of 9.2 and 9.3 GHz is injected to the MZM2. As shown in Fig. 4, the SFDR and the noise floor of channel-10 without distillation is 94.2 dB·Hz$^{2/3}$ and -124.5 dBm/Hz, respectively. Meanwhile, the SFDR and the noise floor of channel-10 with distillation is 96.8 dB·Hz$^{2/3}$ and -128.7 dBm/Hz, respectively. The reasons for the high SFDR and low noise floor due to the ASE noise from EDFA and the impurity of the comb which has been suppressed by distillation. Similarly, the measured SFDRs between 94.2 and 96.3 dB·Hz$^{2/3}$ without distillation are obtained in other channels, meanwhile, with distillation the SFDRs between 96.8 and 101.3 dB·Hz$^{2/3}$ are obtained in other channels. The proposed photonic channelization system shows a relative good linearity which may have potential applications in the RF frontends of future systems.

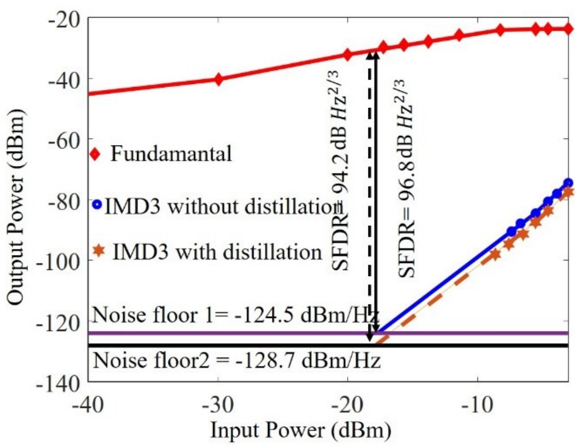
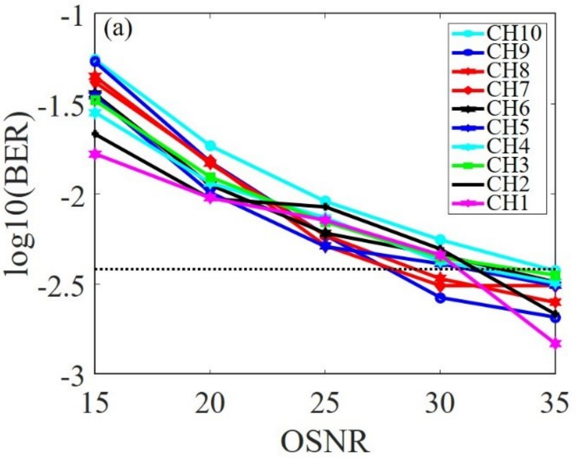


Fig.4. Measured SFDR in channel 10

In order to further verify the demodulation performance of the proposed frequency comb distillation enabling broadband microwave photonic channelized receiver scheme, A multi-band DOF signal covering 2-12GHz is used for testing. Fig. 5 explores the relationship between BER performance as a function of the OSNR with or without distillation. It can be seen that different channel receiver without and with distillation induce a maximum of 7.3-dB and 5-dB OSNR penalty at the 7% FEC threshold of BER =3.8×10^{-3}. Note that with the distillation, the purity of the comb is better than that of without the distillation. Therefore, the OSNR sensitivity with distillation is a bit better than that without distillation (2.3 dB better at BER of 3.8×10^{-3}).



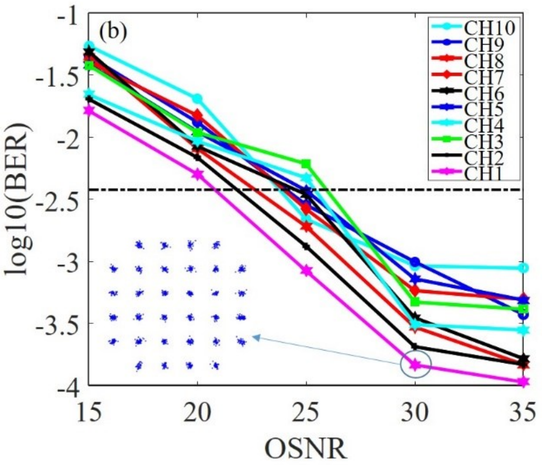


Fig.5. BER versus OSNR: (a) without distillation, (b) with distillation.

V. Conclusion

We have investigated a frequency comb distillation enabling broadband microwave photonic channelized receiver approach for alleviating the broadband noise and the harmonic distortion. By designing the FSR of the MRR to match the line spacing of the micro-comb effectively, a 10-GHz bandwidth RF signal with frequencies from 2 to 12 GHz is down-converted to the same IF band with 1-GHz instantaneous bandwidth, where the in-band crosstalk suppression of large than 30 dB for all channels and the spurious-free dynamic range of the system can reach 101.3 dB • $Hz^{2/3}$. Moreover, BERs for all channels without and with distillation are compared.

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