IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 4, Number 4, August 2012

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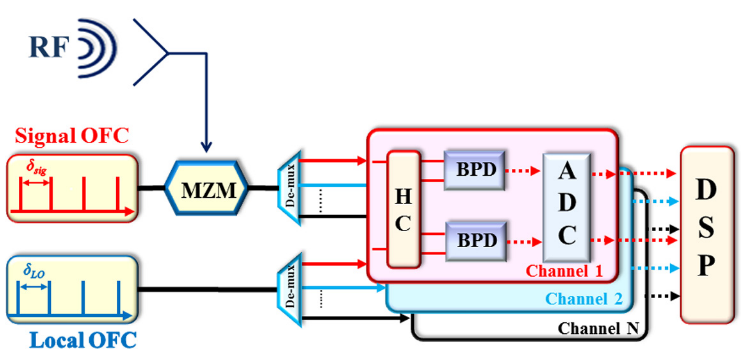

DOI: 10.1109/JPHOT.2012.2207380

Broadband Photonic RF Channelization Based on Coherent Optical Frequency Combs and I/Q Demodulators

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DOI: 10.1109/JPHOT.2012.2207380
1943-0655/$31.00 ©2012 IEEE

Manuscript received May 22, 2012; revised June 27, 2012; accepted June 28, 2012. Date of current version July 12, 2012. This work was supported in part by the National 973 Program under 2012CB315705, by the 863 Program under 2011AA010306, by the NSFC under Programs 61107058 and 61120106001, and by the Beijing Excellent Doctoral Thesis Project under Grant YB20101001301.
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Abstract: In this paper, a novel photonic-assisted broadband and high-resolution radio-frequency (RF) channelization scheme based on dual coherent optical frequency combs (OFCs), regular optical de-muxes, and I/Q demodulators is analyzed and experimentally demonstrated. The use of two coherent combs avoids precise optical alignment, and a numerical filter in digital signal processor (DSP) enables an ideal rectangular frequency response in each channel without any ultranarrow optical filters. Besides, due to the use of I/Q demodulators, ambiguous frequency estimate in direct detection is avoided. By using two coherent OFCs with the free spectrum range (FSR) of about 40 GHz, we experimentally demonstrate the channelization scheme with seven channels, 500-MHz channel spacing, and frequency coverage from 3.75 to 7.25 GHz. The input RF tones are accurately downconverted to an intermediate frequency (IF) with a maximum frequency error of 125 kHz. Meanwhile, the channel frequency response and crosstalk of the scheme are also evaluated experimentally.

Index Terms: Microwave photonics signal processing, fiber optics systems, I/Q demodulation.

1. Introduction

The military RF receivers for combat, reconnaissance, and surveillance are desired strongly to provide threat information more accurately and more rapidly [1]. The traditional analog-component-based military RF receiver, limited by large size, weight, and power (SWaP), is gradually replaced by digital receiver, with high flexibility, low cost, and high precision [2]. However, nowadays, applications drive the receiver toward higher frequencies and larger bandwidths, which poses a significant challenge to digital RF receiver due to limited sampling ratio of ADC (about $\sim$GHz). Furthermore, even if ADC technology could be developed to meet the application needs, resulting data volume would pose huge challenges to downstream DSP. Therefore, it is essential to provide a means to channelize the broadband signal spectrum into frequency channels whose bandwidths are compatible with digital electronics.

Photonic technologies have made enormous strides in recent years since it owns advantages such as high frequency, large bandwidth, and being considered as an approach to process ultrawideband RF signals [3]. Several innovative photonic-assisted RF channelizer approaches

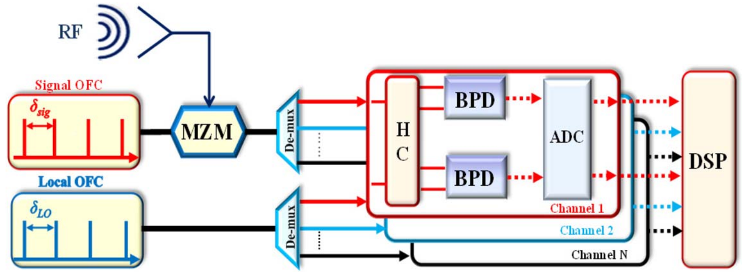

Fig. 1. Configuration of the coherent OFC-based channelization scheme.

have been proposed and demonstrated, based on Bragg-grating Fabry–Perot cavities [4], Bragg-grating arrays [5], acousto-optic channelizer [6], free-space diffraction grating [7], parallel filter banks [8], two FP filters with different FSRs [9], integrated magneto-optic devices [10], integrated optical channelizer [11], and so on. Most of the schemes were realized by an upconversion-and-split topology, where the RF signal was modulated on an optical carrier and then was split into *N* ways by *N* physically distinct filters. However, the bandwidths of the split subchannels are limited by electronic hardware, and large numbers of narrow, spectrally dense, and precisely centered optical filters are needed. The requirement of flattop and steep-edge amplitude response in each sub-channel further increases the fabrication difficulty. The precise alignment between optical source and narrow filters also limits practical applications. Additionally, due to square law feature of photo-detector (PD), direct detection [12] or partial coherent detection results in ambiguous frequency estimation.

In this paper, a novel photonic-assisted RF channelization scheme based on two optical frequency combs (OFCs), regular optical de-muxes, and I/Q demodulators is proposed and characterized. The input broadband RF signal is upconverted and multicast by optical lines in the first OFC. These copies are then physically separated by a regular optical de-mux, each of which is mixed with the other channelized OFC. Due to the difference of the free spectrum ranges (FSRs) of the two combs, different spectrum slices of the RF signal are extracted and downconverted to baseband or IF by the followed I/Q demodulators. Compared with previous proposals, the coherence of the two combs enables stable and precise channelization without active optical source–filter alignment; the numerical filter in DSP also enables ideal amplitude response in each channel and seamless covering over a broad band, avoiding the use of arrayed ultranarrow optical filters. Meanwhile, I/Q demodulation provides an accurate frequency location. Experimentally, two ~40-GHz coherent OFCs are obtained with flat and multiple frequency lines with high optical signal-to-noise ratio (OSNR). As a proof of concept, a channelization scheme with seven channels, 500-MHz channel spacing, and frequency coverage from 3.75 to 7.25 GHz is demonstrated. The channelization capacity is analyzed theoretically, and the channel response and crosstalk are evaluated in experiment.

2. Operation Principle of the Channelization Scheme

The proposed channelization scheme is shown in Fig. 1. Through a Mach–Zehnder modulator (MZM), the signal OFC (with FSR of δ_{sig}) is modulated by the broadband RF signal and then channelized by an optical de-mux with channel spacing of δ_{lo}. In each channel, the signal OFC is demodulated by the corresponding channelized local OFC (with FSR of δ_{lo}; assume that δ_{lo} is slightly different from δ_{sig}) through a standard I/Q demodulator: a 90° hybrid coupler (HC), a pair of balance PDs (BPD) and ADCs, and a DSP unit.

The broadband RF signal channelization process is shown in Fig. 2. The frequency of each line in the signal OFC can be expressed as

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

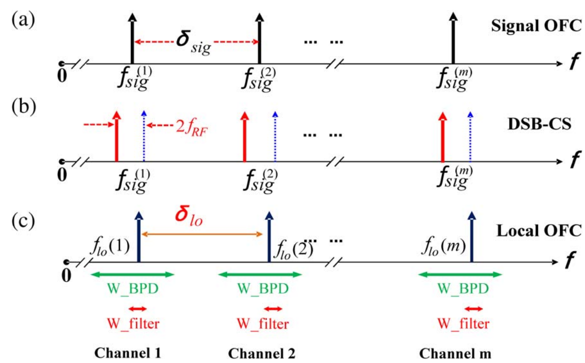

Fig. 2. (a) Spectrum of the signal OFC. (b) The spectrum of the modulated signal OFC. (c) The spectrum of the local OFC. W_BPD: the bandwidth of BPD; W_filter: the bandwidth of the numerical filter in DSP.

where $f_{sig}(1)$ is the frequency of the first line. δ_{sig} and m are the FSR and line number of signal OFC, respectively. Similarly, frequency of the local OFC is given as

$$f_{lo}(n) = f_{lo}(1) + (n-1)\delta_{lo} \tag{2}$$

where $f_{lo}(1)$ is the frequency of the first local line. δ_{lo} and n are the FSR and line number of the local OFC, respectively.

Assume the MZM is driven under small driving voltage and double-sideband carrier-suppression (DSB-CS) modulation [13]. When an RF tone with arbitrary frequency of f_{RF} is fed into the system, it is multicast by the signal comb, and the mth upconverted copy has the frequency of

$$f_{sig\_mod} = f_{sig}(1) + (m-1)\delta_{sig} + f_{RF}. \tag{3}$$

Note that we ignore the -1st order sideband copies, since their mixings with the corresponding local lines exceed the bandwidth of BPDs/ADCs/numerical filters of I/Q demodulators in our design [where $f_{lo}(1) > f_{sig}(1)$ and $\delta_{lo} > \delta_{sig}$, as shown in Fig. 2; also see (7)].

Generally, optical de-mux has sufficient interchannel crosstalk suppression. Therefore, in the mth channel, the I/Q demodulator receives only the mth RF copy and the mth line of the local comb, as shown in Fig. 2(b) and (c). The two optical inputs generate two quadrature optical interference products, which are simultaneously received by two BPDs. The two tributaries (I and Q signals) represent the real and imaginary component of the downconverted tone, respectively, which are then synthesized in the DSP [14]. According to (2) and (3), the received tone (digitalized complex signal) at the mth channel has the frequency of

$$f_{IF}^{m} = f_{center}^{m} - f_{RF} \tag{4}$$

where f_{center}^{m} is the (input) center frequency of the mth channel

$$f_{center}^{m} = \left[f_{lo}(1) - f_{sig}(1)\right] + (m-1)\Delta, \tag{5}$$

and Δ is the (input) channel spacing

$$\Delta = \delta_{lo} - \delta_{sig}. \tag{6}$$

In our scheme, the bandwidth of BPDs and ADCs is (slightly) larger than Δ; in the DSP, a numerical rectangular-type filter with bandwidth of exactly Δ and centered at 0 is employed. Then, the amplitude response of the mth channel is

$$A_{IF}^{m} = \text{rect}(f_{IF}^{m})\begin{cases} 1, & \left|f_{IF}^{m}\right| < \Delta/2 \\ 0, & \text{others.} \end{cases} \tag{7}$$

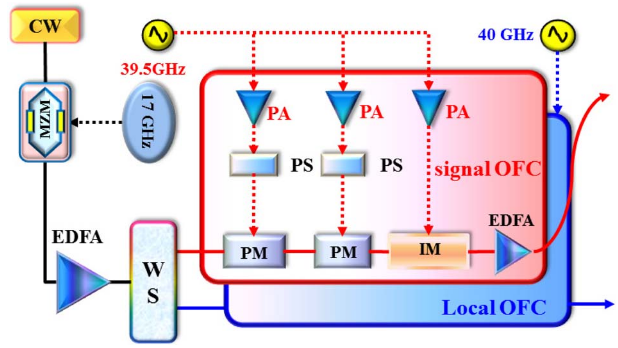

Fig. 3. Experiment setup for coherent combs generation based on phase and intensity modulation.

Since the proposed channelizer is a linear time-invariant (LTI) system for each channel (except the downconversion), (7) stands for any signal with data modulation. For example, a signal with bandwidth larger than Δ will be sliced and output at different channels; such slicing and outputting are ruled by (7). Note that we assume $\delta_{\text{sig}} < \delta_{\text{lo}}$; the scheme also works for $\delta_{\text{sig}} > \delta_{\text{lo}}$, while the corresponding equations should be changed.

Different from other reported channelizers [9], [12], the optical de-mux in our scheme is employed to physically separate the multicast RF channels, rather than filter and spectrally shape them. The channel bandwidth of the channelizer, Δ (hundreds of megahertz), is much less than the channel bandwidth spacing of the optical de-mux (δ_{lo}, tens of gigahertz). The alignment tolerance between the optical source and de-mux is then as large as a few gigahertz, which can be obtained by regular and individual temperature control. Therefore, the precise source–filter alignment is avoided. So is the ultranarrow or specially designed optical filtering, because the narrow-bandwidth filtering and precise spectral shaping are performed by the band-limited BPDs/ADCs and numerical filters. According to (7), the proposed channelizer can seamlessly cover a broad band while each channel has an ideal rect-shaped amplitude response, which is hardly achieved by optical filtering.

In order to avoid the interference from the -1st order sideband of the neighboring channel, the bandwidth of the detectable RF signal is limited as

$$0 < f_{\text{RF}} < \delta_{\text{sig}}/2. \tag{8}$$

According to (6) and (8), the maximum channels of the scheme are

$$N < \frac{\delta_{\text{sig}}/2}{\Delta}. \tag{9}$$

3. Generation of Dual Coherent OFCs

In our scheme, the photonic RF channelization scheme is based on dual coherent combs. Such combs can be generated by modulating two coherent seeds through cascaded phase and intensity modulators [15], as shown in Fig. 3. A continuous-wave (CW) light (from Koheras AdjustiK Benchtop Fiber Laser, centered at 1550.83 nm with linewidth < 1 kHz and power of 15 dBm) is modulated by an MZM with an $f_c = 17$ GHz sinusoidal wave (from Anritsu Synthesized CW Generator) under DSB-CS condition. By the WaveShaper (Finisar 4000S), two sidebands with frequency spacing of 34 GHz ($2f_c$) are separated as the coherent seeds. Each seed is fed into two cascaded phase modulators (PMs), which are modulated by the microwave tone with frequency of $\delta_{\text{sig}} = 39.5$ GHz or $\delta_{\text{lo}} = 40$ GHz. The driving voltages of the PMs are set as large as possible to increase the line number. Two intensity modulators (IMs) are used to flatten the combs, and microwave phase shifters are applied to synchronize these microwave tones applied on the modulators. Stable channelization is ensured by the two combs since δ_{lo}, δ_{sig}, and $f_{\text{lo}}(1) - f_{\text{sig}}(1)$ are all determined by the microwave sources that are free from environmental condition.

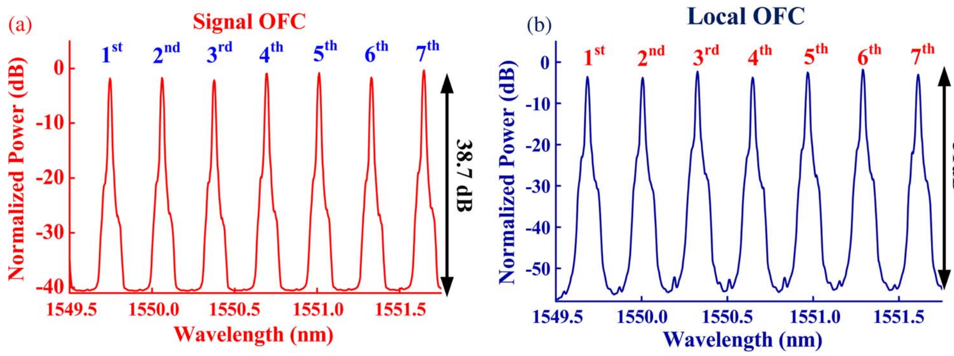

Fig. 4. Spectrums of the generated signal and local OFC.

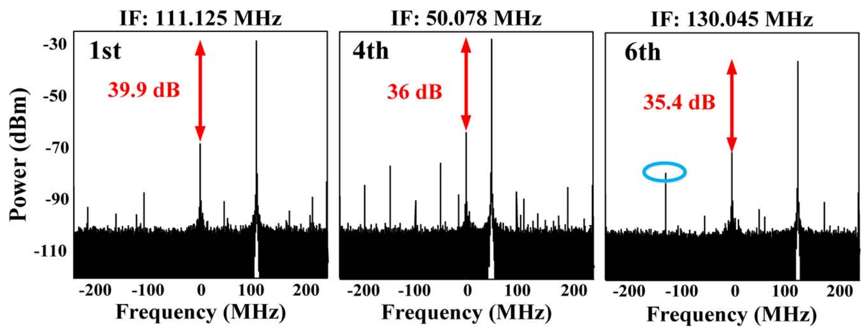

Fig. 5. Output of the first, fourth, and fifth channels when RF signals of 4.111, 5.55, and 6.63 GHz are inputted, respectively.

The generated OFCs are measured by an optical spectrum analyzer (OSA: YOKOGAWA AQ6370B optical spectrum analyzer with resolution bandwidth of 0.02 nm), as shown in the Fig. 4. Within 3-dB bandwidth, seven lines in each comb are obtained with the OSNR about 40 dB and FSR of 40 or 39.5 GHz, ranging from 1549.5 to 1551.75 nm. Note that the different OSNRs of the two combs come from the different extinction ratio of the IMs; the slightly unflattened combs may cause uneven among-channel amplitude response, which can be compensated in DSP.

According to (8), the 40-GHz FSR provides the maximum sensible RF frequency up to 20 GHz. OFCs with large FSR and large number of lines are desired for high channelization capacity, which has been demonstrated by other generation techniques [16]–[18]. Especially, the "Kerr comb" by on-chip micro-resonator can pave the way for the small size, simple and broadband channelizer [17], [18].

4. Experiment and Result

The proposed photonic RF channelization is experimentally demonstrated. As a proof of concept, two WaveShapers (Finisar 1000S) are used instead of the optical de-muxes, and an I/Q demodulator measures each channel in turn by tuning the WaveShapers. For the availability of our equipment, two 10-GHz BPDs $(\mathrm{u^2t})$ and a real-time sampling oscilloscope (LeCroy WavePro 7400A with 8-bit resolution) are used. Note such high speed is not a must: since the channel spacing (Δ) is 500 MHz, the bandwidths of BPDs and ADCs are only required to be $<$ 500 MHz. The acquired data are processed by an offline program where each tributary is filtered by a rect function centered at 0 and with bandwidth of $\Delta = 500$ MHz before I/Q data synthesis. $f_{\mathrm{lo}}(1) - f_{\mathrm{sig}}(1) = 4$ GHz; according to (5), our channelizer equally divides 3.75 GHz to 7.25 GHz band seamlessly by seven channels.

We test the scheme by inputting single RF tone with 4.111, 5.55, and 6.63 GHz, respectively. The downconverted IF tone is expected to be 111, 50, and 130 MHz in theory, which appears in the 1st, 4th, and 6th channel, respectively. In experiment, the IF tone is digitalized with the sampling rate of 5 Gs/s and sampling time of 100 μs. Then, the spectrum is calculated offline and shown in Fig. 5.

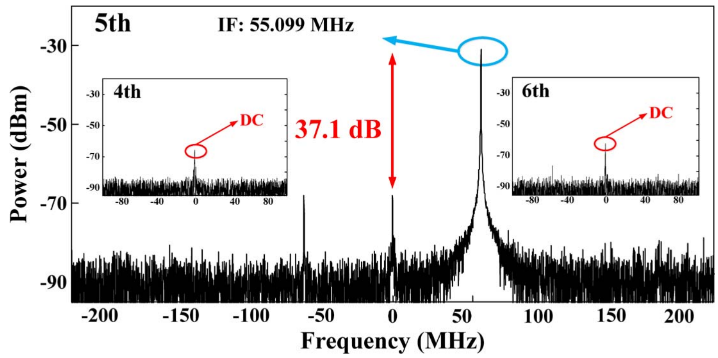

Fig. 6. Output of the 4th, 5th, and 6th channels when 6.055-GHz signal is inputted.

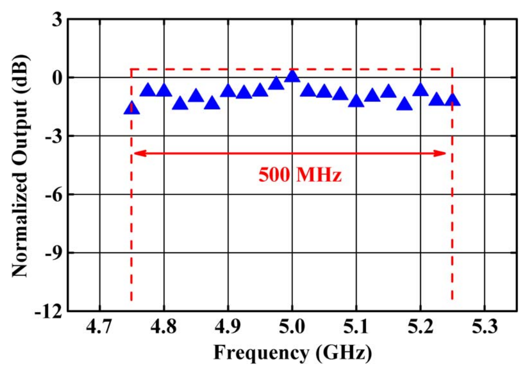

Fig. 7. Normalized channel response of the 3rd channel with center frequency of 5 GHz and channel width of 500 MHz.

We can observe that each RF tone is correctly downconverted and channelized exactly as the theory predicts. The IF frequency errors (< 125 kHz) originate from the frequency errors of our microwave sources. Note that spurious tones (located at the harmonic components of the detected IF) come from: 1) slight phase and amplitude mismatch between I and Q tributaries; 2) nonlinearity of the real-time sampling oscilloscope.

The crosstalk and frequency response of the channelization scheme are measured. In theory, due to the ideal rectangle filtering response of the numerical filter, the crosstalk of out-of-channel can be removed. In our experiment, the input RF tone is 6.055 GHz (the corresponding IF locates in the 5th channel). Then, the outputs of 5th channel and the next-nearest neighbor channels (4th and 6th channels) are measured and shown in Fig. 6. No related IF tones are observed in the 4th and 6th channels, which is in good agreement with the theoretical analysis. But in both channels, there is a small dc component, which comes from the imbalance of the BPDs.

To measure the channel frequency response, a sweeping RF tone is applied to the MZM. The 3rd channel is measured from 4.75 to 5.25 GHz with a 25-MHz step. The normalized amplitude response is shown in Fig. 7. One can observe that the channel response is a rectangle-type function: 1) inside the channel, the proposed channelization scheme has fine channel response uniformity (< 1.44 dB); 2) out of the channel, no IF is outputted, which agrees with analysis in theory.

5. Conclusion

We demonstrated theoretically and experimentally a dual-coherent-OFC-based RF channelization scheme with seven channels, 500-MHz channel spacing, and frequency coverage from 3.75 to 7.25 GHz. Seamless frequency coverage and rectangular frequency response in each channel were reported. Coherent combs and numerical filters avoid the use of ultranarrow optical filtering and precise optical source–filter alignment. Besides, the scheme can be tuned simply by adjusting f_c, $\delta_{\rm lo}$, and $\delta_{\rm sig}$. The advantage also includes integrated downconversion as well as precise and unambiguous RF frequency measurement by the I/Q demodulation.

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