Multichannel Up-Conversion Based on Polarization-Modulated Optoelectronic Oscillator

Dan Zhu, *Member, IEEE*, Shifeng Liu, and Shilong Pan, *Senior Member, IEEE*

***Abstract*— Photonic microwave multichannel up-conversion based on a polarization-modulated optoelectronic oscillator is proposed and demonstrated. The scheme produces a high-quality local oscillation signal, implements photonic microwave multichannel up-conversion at arbitrary optical wavelengths, and realizes dispersion penalty compensation for multichannel radio over fiber links with different transmission distances in different channels simultaneously. An experiment is carried out. The 50-Mb/s 16 QAM signals at 3.5 and 7.5 GHz are successfully up-converted to 13.436 and 17.436 GHz, and transmitted over 20- and 15-km fibers with dispersion-induced power penalty removed in two independent channels, respectively. The phase noise curves with or without IF signals applied are superimposed, with the value being lower than −110 dBc/Hz at 10-kHz offset.**

***Index Terms*— Optoelectronic oscillator, multichannel, up-conversion, dispersion, power penalty, radio over fiber.**

I. Introduction

RADIO-OVER-FIBER (RoF) systems which can transmit microwave signals over long-distance optical fibers, have been investigated intensively for the applications including broadband wireless communications, antenna remoting, radars and satellite communication systems [1]–[4]. Wideband frequency up-conversion and dispersion-free transmission of the up-converted signal over long-distance optical fibers are two of the key technologies in RoF systems [1]. Conventionally, the frequency up-conversion can be realized by mixing an electrical local oscillator (LO) with an intermediate-frequency (IF) signal at an electronic mixer. This approach, however, always suffers from limited bandwidth, large conversion loss and incapability of multichannel operation. In addition, the high-frequency LO generated in the electronic domain always has relatively poor phase noise performance. To overcome these problems, several photonic approaches to realize the frequency up-conversion in the optical domain have been reported [4]–[9], among which the frequency up-conversion based on an optoelectronic oscillator (OEO) is of great interests because the OEO can simultaneously serve as a low phase noise LO and perform multichannel frequency up-conversion [10]–[12]. In [13], a frequency-doubling OEO has been proposed to perform the frequency up-conversion using optical-carrier-suppressed (OCS) modulation, but two fixed wavelengths in the 1310- and 1550-nm band must be carefully selected to implement the frequency-doubling OEO, and the transmission distance of the OCS modulation signal in the optical fiber is limited due to the dispersion-induced power penalty. In [14], we reported an optical up-conversion scheme using a polarization modulator (PolM) based OEO. Only one laser with arbitrary wavelength is need. In addition, a frequency-quadrupling OEO based on polarization-modulation is proposed to upconvert baseband signals to the millimeter-wave band using only low-frequency devices [15]. The key limitation of the two approaches is that the upconverted signal is a double-sideband modulated signal, which would undergo serious dispersion-induced power penalty when transmitted in a long-distance optical fiber. Recently, an OEO incorporating a dual-parallel Mach-Zehnder modulator (DPMZM) is used to implement photonic RF up-conversion. The key advantage of the approach is that the dispersion-induced power fading can be removed by properly setting the DC bias of the DPMZM because the upconverted signal is a carrier phase-shifted double sideband modulation signal [16]. However, one DC bias only corresponds to a certain transmission distance. That is to say, once the DC bias is fixed, the transmission distance should also be fixed. This feature is extremely unacceptable in multichannel system with different transmission distances for different channels. Recently, a novel integrable modulator consisting of a PolM and a polarizer is proposed for analog photonic links to compensate the power fading at any frequency of interest by adjusting a polarization controller (PC) placed before the modulator [17]. However, the simultaneous realization of multichannel frequency up-conversion and dispersion-free transmission of multichannel signals, i.e. two of the essential functions in multichannel radio-over-fiber systems, can not be realized.

In this Letter, a novel photonic microwave multichannel up-conversion scheme based on a polarization-modulated OEO is proposed, which enables simultaneously high-quality

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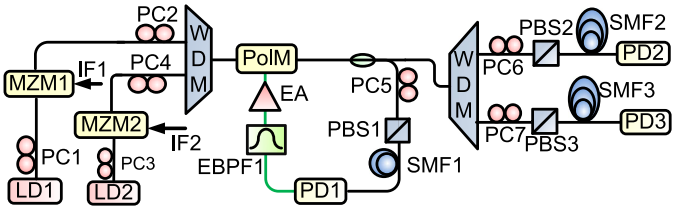

Fig. 1. Schematic diagram of the proposed multichannel up-conversion based on polarization-modulated optoelectronic oscillator. LD: laser diode; PC: polarization controller; MZM: Mach-Zehnder modulator; PolM: polarization modulator; WDM: wavelength division multiplexer; PBS: polarization beam splitter; SMF: single-mode fiber; EBPF: electrical bandpass filter; EA: electrical amplifier; PD: photodetector.

LO generation, multichannel frequency up-conversion and dispersion-free transmission of multichannel signals with different transmission distances in different channels. A proof-of-concept experiment is carried out. 50-Mbps 16 QAM signals at 3.5 and 7.5 GHz are successfully up-converted to 13.436 and 17.436 GHz, and transmitted over 20- and 15-km fiber with the dispersion-induced power penalty compensated, respectively. In addition, the injected IF signals have almost no influence on the phase noise performance of the oscillation signal in the loop.

II. Principle

The schematic diagram of the proposed photonic microwave multichannel up-conversion scheme based on a polarization-modulated OEO is shown in Fig. 1. Two lightwaves with different wavelengths from two laser diodes (LDs) are modulated by two IF signals to be up-converted at two MZMs, respectively. The two optical microwave signals are multiplexed by a wavelength division multiplexer (WDM) and directed to a PolM. A PC is inserted in each channel to align the polarization direction of the signal to have an angle of 45° to the principal axes of the PolM. A 30%:70% optical coupler is connected to the PolM to split the polarization-modulated signal into two branches. The lower branch with 70% optical power is used to form the oscillation loop of the OEO. A PC (PC5) and a polarization beam splitter (PBS; PBS1) is served as a polarizer with its principal axis oriented at an angle of 45° to one principal axis of the PolM, and a static phased term of $\pi/2$ is also introduced. In this way, the output of PBS1 is a linearly intensity modulated signal [18]. A length of single-mode fiber (SMF) is introduced in the loop as the energy storage element to realize a large energy-decay time needed for a high-Q oscillation [19]. A photodetector (PD, PD1) is used to perform optical-to-electrical conversion. The electrical signal is filtered by a high-Q electrical bandpass filter (EBPF, EBPF1), amplified by a low noise electrical amplifier (EA), and then fed back to the RF port of the PolM to form an oscillation at ω_{osc}.

In the upper branch, after the WDM, up-converted signals at $\omega_{osc} + \omega_{IF1}$ and $\omega_{osc} + \omega_{IF2}$ will be generated in each channel because of the optical mixing in the PolM. In order to compensate the dispersion, another PC is inserted in each channel to align the principal axis of the PBS to have an angle of α to one principal axis of the PolM. After transmission over a length of SMF, the optical signal is introduced to a PD to produce the desired electrical up-converted signal.

The PolM is a special phase modulator supporting both TE and TM modes with opposite phase modulation indices [12]. Take one channel for example, in the upper branch, by tuning PC6 to change α, the PolM together with the PC and the PBS in the corresponding output channel performs amplitude modulation and phase modulation with ratio between them changed. Similar to the polarization modulation employed in [17], the function between the power of the up-converted signal at ω_{osc}+ω_{IF} and the angle α between the principal axis of the PBS in the output channel and one principal axis of the PolM can be expressed as

$$P \propto \sin^2[2\alpha + \frac{1}{2}\beta''(\omega)L(\omega_{OSC} + \omega_{IF})^2] \tag{1}$$

where $\beta''(\omega)$ is the second-order derivative of the propagation constant with respect to the optical angular frequency, which represents the dispersion of the transmission link, and L is the transmission distance.

Dispersion-induced power fading at the frequency of the up-converted signal will be compensated when α is tuned by setting PC in the output channel to make

$$2\alpha + \frac{1}{2}\beta''(\omega)L(\omega_{OSC} + \omega_{IF})^2 = \frac{(2k+1)\pi}{2}, \quad k = 0, \pm 1, \pm 2 \cdots \tag{2}$$

Thus, for given ω_{osc}, ω_{IF}, and L, the power of the recovered up-converted signal at ω_{osc}+ω_{IF} can always be adjusted to be maximal by tuning α. As a result, the dispersion-induced power fading can be dynamically compensated by tuning the PC at the output branch. Comparing with the dispersion-induced power fading compensation method based on DPMZM [16], the distinctive feature of the proposed method can be used in multichannel RoF system with different transmission lengths in different channels.

III. Experiment Results and Discussion

An experiment based on the setup shown in Fig. 1 is performed. The major parameters are as follows. The wavelengths of laser source (Agilent N7714A) are set to be 1550.980 and 1549.326 nm; MZM1 (Fujitsu FTM7921ER) has a 10-GHz bandwidth and a 4-V half-wave voltage, while the bandwith and half-wave voltage of MZM2 (Versawave Technologies) are 40 GHz and 3.5 V, respectively; the PolM (Versawave Technologies) has a bandwidth of 40 GHz and a half-wave voltage of 3.9V; the length of SMF1 in the OEO loop is 150 m, and the lengths of SMF2 and SMF3 in the output transmission branches are 15 km and 20 km, respectively. EBPF1 in the OEO loop has a bandwidth of 11.34 MHz centered at 9.936 GHz; the gain of the EA is about 40 dB; PD1 has a bandwidth of 20 GHz and a resposivity of 0.85 A/W; PD2 and PD3 have a bandwidth of 50 GHz and a responsivity of 0.65 A/W. The frequency response of the transmission link is measured by a vector network analyzer (Agilent N5230A), and the electrical spectra and phase noise spectra are observed by an electrical spectrum analyzer (ESA) with a phase noise measurement module (Agilent E4447AU).

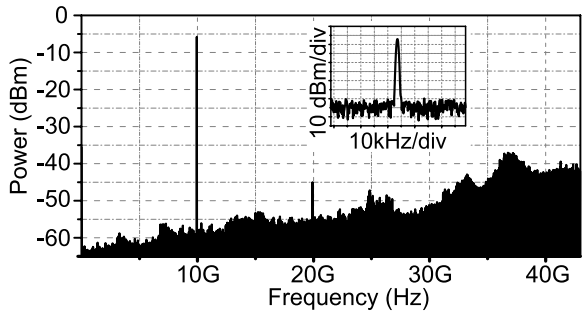

Fig. 2. Electrical spectrum of the oscillation signal in the loop of the OEO. Inset: the zoomed-in view of the 9.936-GHz signal at a span of 100 kHz and a RBW of 9.1 kHz.

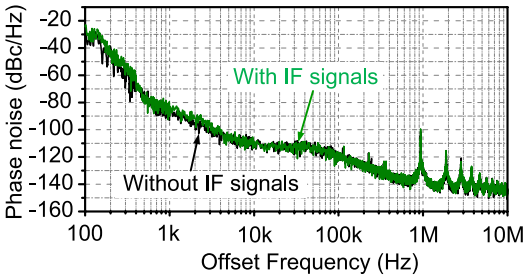

Fig. 3. Single-sideband phase noise spectra of the 9.936-GHz oscillation signal in the OEO loop with and without IF signals applied to the MZMs in the two channels.

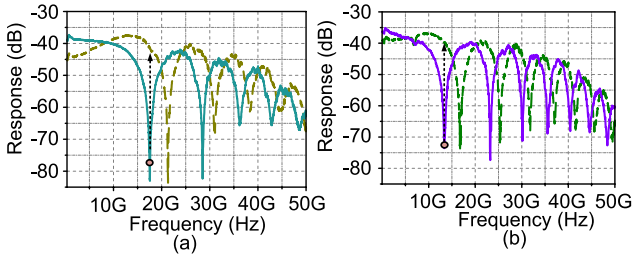

Fig. 4. Frequency responses of the (a) 15-km and (b) 20-km SMF based links with and without dispersion compensation at the output branch.

The IF signal is generated by a vector signal generator (Agilent E8267D), while the up-converted signal is measured and analyzed by a signal analyzer (Agilent N9030A).

The electrical spectrum of the oscillation signal in the OEO loop is shown in Fig. 2. The 9.936-GHz signal is 39.2-dB higher than other harmonics. The zoom-in view of the oscillation signal at a span of 100 kHz and a RBW of 9.1 kHz is also presented in the inset of Fig. 2.

Fig. 3 shows the single-sideband phase noise spectra of the 9.936-GHz oscillation signal in the OEO loop with and without IF signals applied to the MZMs in the two channels. The two curves are superimposed, which proves that the injected vector signals have almost no influence on the phase noise performance of the oscillation signal. The phase noise is lower than -110 dBc/Hz @ 10 kHz offset.

The performance of the multichannel up-conversion and dispersion compensation is also investigated. Fig. 4 shows the frequency responses of the 15- and 20-km SMF-based links with and without dispersion compensation, respectively.

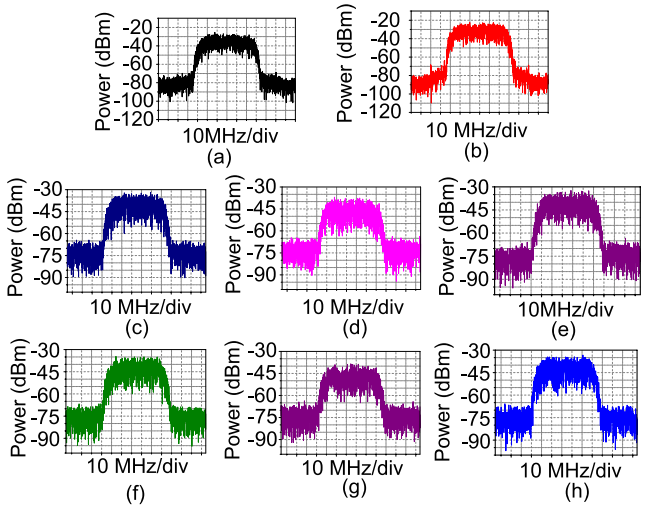

Fig. 5. Electrical spectra of the original 50-Mbps 16 QAM at (a) 7.5 GHz and (b) 3.5 GHz, the received up-converted signal at 17.436 GHz at the conditions of (c) back to back transmission, 15-km SMF transmission (d) without and (e) with dispersion compensation in one channel; and the received up-converted signal at 13.436 GHz at the conditions of (f) back to back transmission, 20-km SMF transmission (g) without and (h) with dispersion compensation in the other channel.

As can be seen, by tuning PC6 and PC7, respectively, the frequency points at around 13.5 and 17.5 GHz (being nearby the center frequency of the up-converted signal in each channel) which undergo serious chromatic dispersion-induced power fading can be tuned to be peak points of the frequency responses.

Fig. 5 shows the electrical spectra of the generated 50-Mbps 16 QAM signals and the received up-converted signals in each channel. As can be seen from Fig. 5(c), the 50-Mbps 16 QAM signal at 7.5 GHz is successfully up-converted to 17.436 GHz. As compared with the spectrum in the case of back to back transmission, after 15-km SMF transmission, the dispersion-induced power penalty is about 6 dB, as shown in Fig. 5(d). With the dispersion compensation by tuning PC6, the dispersion induced power penalty is almost removed, as shown in Fig. 5(e). In the other channel, the signal at 3.5 GHz is up-converted to 13.436 GHz. With 20-km SMF transmission, the up-converted signal has a power penalty of about 4 dB. By tuning PC7, again, the power penalty is removed.

The error vector magnitude (EVM) test results of the up-converted signals in each channel in different conditions are shown in Fig. 6. Applying the EVM threshold 5.6% for 16 QAM signal [20], the transmissions of the up-converted signals over 15-km SMF and 20-km SMF without dispersion compensation have a power penalty of about 7.6 dB and 6.6 dB as compared with the back to back transmission condition, respectively. In the dispersion compensation condition, as can be seen, the up-converted signals can be transmitted over 15-km and 20-km SMF with almost no power penalty in both channels. Effective dispersion compensation is realized and the EVM performance is improved. The quality of the up-converted 16 QAM signal is still good enough with EVM under 5.6% when the received optical power is -6 dBm in both

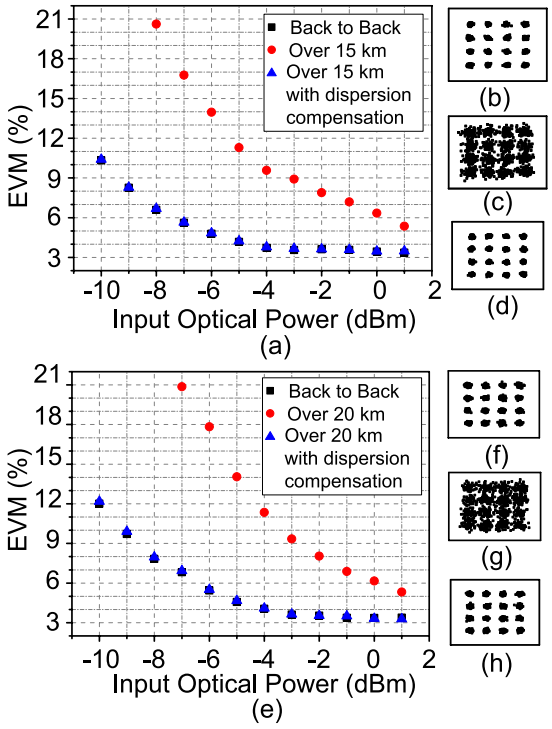

Fig. 6. (a) Error vector magnitude (EVM) versus received optical power for 50-Mbit/s 16 QAM signal at 17.436 GHz at the conditions of back to back transmission, 15-km SMF transmission without and with dispersion compensation; IQ constellation when the optical power is −6 dBm at the conditions of (b) back to back transmission, 15-km SMF transmission (c) without and (d) with dispersion compensation in one channel. (e) EVM versus received optical power for 50-Mbit/s 16 QAM signal at 13.436 GHz at the conditions of back to back transmission, 20-km SMF transmission without and with dispersion compensation; IQ constellation when the optical power is −6 dBm at the conditions of (f) back to back transmission, 20-km SMF transmission (g) without and (h) with dispersion compensation in the other channel.

channels. IQ constellation when the optical power is -6 dBm in different conditions are also shown, which proves the quality improvement of the up-converted 16 QAM signal transmitted over 15-km and 20-km with dispersion compensation in both channels. It should be noted that the state of polarization and the power variation of the optical signals to the OEO would affect the power of the oscillation signal and the performance of the photonic microwave up-conversion. To overcome this problem, the electrical amplifier in the OEO loop is operated at the gain saturation regime.

IV. CONCLUSION

We proposed and demonstrated a photonic microwave multichannel up-conversion based on a polarization-modulated OEO, to perform multichannel up-conversion of IF signals and transmission of the multichannel up-converted signals with dispersion penalty compensated. Due to the high-Q EBPF in the OEO loop, the injected IF signals have almost no influence on the phase noise performance of the oscillation signal in the loop. The dispersion-induced power penalty for the up-converted signal over long-distance optical fiber transmission can be compensated by simply setting a polarization controller in each channel. 50-Mbps 16 QAM signals at 3.5 and 7.5 GHz are successfully up-converted to 13.436 and 17.436 GHz, and transmitted over 20- and 15-km fiber with dispersion-induced power penalty compensated, respectively. The system can be used in multichannel RoF systems with different transmission lengths in different channels, which can find applications in distributed antenna systems for wireless communication, radars, and satellite systems.

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