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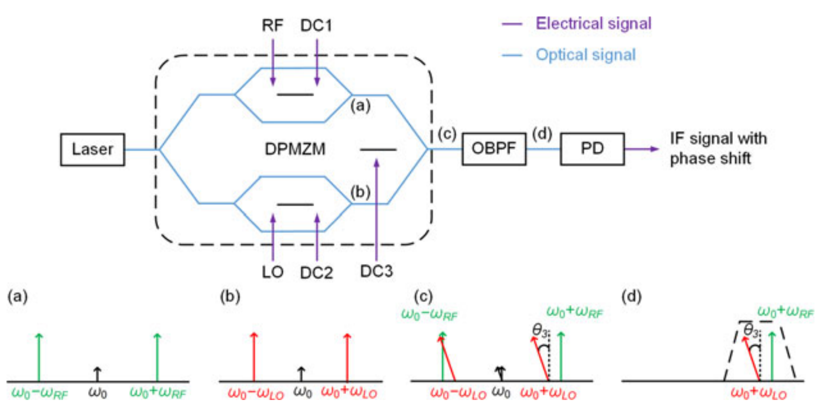

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All-Optical Microwave Photonic Downconverter With Tunable Phase Shift

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Abstract: An all-optical microwave photonic frequency downconverter with tunable full range continuous phase shift is presented. In the proposed system, the radio frequency (RF) and local oscillator (LO) signals modulate two sub Mach–Zehnder modulators (MZMs) in an integrated dual-parallel MZM (DPMZM), respectively. The two sub-MZMs are both biased at the minimum transmission point to implement the carrier-suppressed double-sideband modulation. An optical bandpass filter is then used to retain the +1st order RF and LO sidebands. When the two sidebands are send to a photodetector, an intermediate frequency (IF) signal is produced, and the phase of the converted IF signal is linearly changed by adjusting the bias voltage of the parent MZM in the DPMZM. An experiment is carried out. An RF signal can be downconverted to a phase-tunable IF signal, and the measured spurious-free dynamic range reaches 100.2 dB·Hz$^{2/3}$. The phase deviation and power ripple of the IF signal are less than 2° and 0.26 dB, respectively. The all-optical design makes the system bandwidth unlimited by electrical components. Meanwhile, since the proposed microwave photonic link can simultaneously implement frequency downconversion and full range phase shift of the converted IF signal, it provides a compact alternative for the applications including radio-over-fiber system and phased-array beamforming.

Index Terms: Fiber optics links and subsystems, radio frequency photonics, analog optical signal processing.

1. Introduction

Microwave photonics (MWP), as a new interdisciplinary subject, combines microwave and fiber optics to create a new communication system [1]. Owing to the advantages of wide bandwidth, low loss, and immunity to electromagnetic interference (EMI) in comparison to the conventional electrical devices, microwave photonic links based frequency downconverter, phase shifter and filter have become more and more appealing and been applied in radio-over-fiber (RoF) system, phased-array beamforming and high-speed signal processing, etc [1]–[5].

As the increasing of the carrier frequencies in microwave communication systems, detection and digitization of the high-frequency signal with good resolution and low noise become a significant challenge. Generally, microwave photonic downconverter, which is used to convert the high-frequency signal to an intermediate frequency (IF) signal, is regarded as one of the most effective solutions. Many schemes have been reported about microwave photonic downconverter [6]–[14]. Two Mach-Zehnder modulators (MZMs) have been cascaded to downconvert the radio frequency (RF) signal, which is characterized by high isolation between the RF and the local oscillator (LO) signals [6]. Serial phase modulators (PMs) can be implemented for both downconversion and linearization by using dual-wavelength lasers and optical filter (OF) [7] or using polarization manipulation [8]. A frequency downconverter based on a MZM and a PM in series can be linearized by employing balanced detection and digital signal post-processing [9]. As the waveguide integrated technology develops rapidly, various commercial electro-optic modulators composed of multiple sub-PMs or MZMs have emerged, and have been applied in frequency downconversion. A single dual-drive MZM (DMZM) is designed as a frequency downconverter with a simple setup [10]. A pure IF electrical spectrum is acquired by a multi-octave frequency downconverter through the carrier-suppressed single-sideband (CS-SSB) modulation [11]. A dual-parallel MZM (DPMZM) with an OF can achieve downconversion with superior conversion efficiency and spurious-free dynamic range (SFDR) [12], here the OF is only used to suppress the amplified spontaneous emission (ASE) noise. Besides, optical frequency comb generator and a MZM in parallel can also be applied in downconversion for the ultra-broadband RF signal [13].

In addition to the microwave downconversion, microwave photonic phase shifter, which is employed to manipulate the phase of RF signal, is also widely used to process high-frequency signal. Comparing with the conventional microwave phase shifter, microwave photonic phase shifter possesses broad bandwidth, high tuning resolution and full range of phase shift. A DPMZM and an OF can be associated for the phase shift of high-frequency RF signal directly [14]. A microwave photonic phase shifter is presented based on a DPMZM and an electrical 90° hybrid coupler [15], in which a SSB optical signal is generated without OF. A phase shifter is designed by using a DMZM and an electrical frequency doubler [16]. In this system, a RF signal with phase shift is obtained by beating between the +1st order optical signals of original and frequency-doubled RF signal. However, the frequency of RF signal is restricted due to electrical components [15], [16]. A microwave photonic phase shifter is proposed to realize both the ultra-wide bandwidth phase shift and the amplitude control for RF signal [17]. Except above approaches of heterodyne mixing, other microwave photonic phase shifters based on vector sum [18], slow and fast light effect in semiconductor optical amplifier [19], polarization modulation [20] and stimulated Brillouin scattering effect in optical fibers [21] are also reported.

However, most of the previously reported MWP system use independent sub-systems to process the frequency and phase of the RF signal, respectively. In fact, it is desirable to simultaneously operate both frequency and phase in practical applications, like phased-array beamforming. Microwave photonic links with compact functions have been investigated recently [22]–[24]. A frequency-multiplying microwave photonic phase shifter with independent multichannel phase shift is proposed based on a dual-polarization DPMZM, a polarization controller and a polarizer [22]. It can implement double or quadruple frequency with full range phase shift. A DMZM and an OF have been applied to frequency downconversion with tunable wideband phase shift [23]. Since only the DC bias of DMZM is chosen to produce phase shift where the useless carrier cannot be suppressed. Though the OF is applied, these uninterested optical signals cannot be removed completely and will worsen the purity of IF signal [11].

In this paper, an all-optical microwave photonic downconverter with tunable phase shift is proposed by using a DPMZM and an optical bandpass filter (OBPF). The RF and LO signals drive the top and bottom sub-MZMs of the DPMZM, respectively. The CS double-sideband (DSB) modulation is performed by controlling the DC voltages of the two sub-MZMs, respectively. Then the OBPF is employed to retain the +1st order sidebands of the RF and LO optical signals. Other useless sidebands and residual carrier can be suppressed under the noise floor owing to the combined action of CS-DSB modulation and OBPF. By sending the RF and LO sidebands to a photodetector

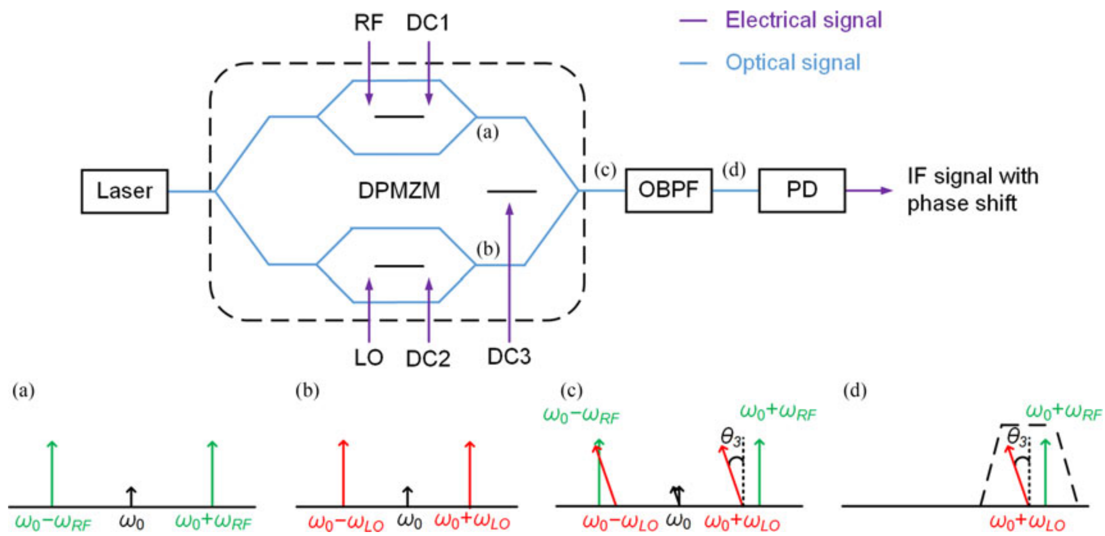

Fig. 1. Schematic diagram of the all-optical microwave photonic downconverter with tunable phase shift and corresponding optical spectral illustrations. (a) - (d) are optical spectrums at different locations.

(PD), an IF signal is produced, and its phase can be linearly shifted by adjusting the bias voltage of the parent MZM in the DPMZM. The power of the IF signal and SFDR of the proposed system are both tested. The phase and power responses of the downconverter are also evaluated. Results show that two functions including frequency downconversion and phase shift are integrated into a microwave photonic link with good stability.

2. Topology and Operation Principle

The schematic diagram of the all-optical microwave photonic downconverter with tunable phase shift is shown in Fig. 1. The system consists of a laser source, a DPMZM, an OBPF and a PD. In the DPMZM, there are two parallel sub-MZMs lying on two arms and a parent MZM driven by DC bias voltages DC1, DC2 and DC3, respectively. Laser provides the optical carrier, and the RF and LO signals are fed to the top and bottom sub-MZMs, respectively. The two sub-MZMs are both operated at the minimum transmission point to achieve the CS-DSB modulation. Then, an OBPF is used to remove the residual optical carrier and other sidebands. Only the $+1$st order RF and LO sidebands are retained. Finally, an IF signal is generated by frequency-beating in a square-law PD. Fig. 1(a)–(d) are optical spectral illustrations at different locations.

A continuous lightwave as optical carrier is launched into the DPMZM. The optical field of two sub-MZMs can be described by [25]

$$E_{\text{top sub—MZM}}(t) = \sqrt{\frac{P_0}{8}} e^{j\omega_0 t} \left[e^{j(m_{\text{RF}} \cos \omega_{\text{RF}} t + \theta_1/2)} + e^{-j(m_{\text{RF}} \cos \omega_{\text{RF}} t + \theta_1/2)} \right] \quad (1)$$

$$E_{\text{bottom sub—MZM}}(t) = \sqrt{\frac{P_0}{8}} e^{j\omega_0 t} \left[e^{j(m_{\text{LO}} \cos \omega_{\text{LO}} t + \theta_2/2)} + e^{-j(m_{\text{LO}} \cos \omega_{\text{LO}} t + \theta_2/2)} \right] \quad (2)$$

where P_0 and ω_0 are the power and the angular frequency of optical carrier, respectively. ω_{RF} is the angular frequency of RF signal and ω_{LO} is the angular frequency of LO signal. $m_{\text{RF}} = \pi V_{\text{RF}}/V_\pi$ is the modulation depth of the sub-MZM on the top arm, and $m_{\text{LO}} = \pi V_{\text{LO}}/V_\pi$ is the modulation depth of the sub-MZM on the bottom arm. $\theta_1 = \pi V_{\text{DC1}}/V_\pi$ is the optical phase difference between the arms of top sub-MZM, and $\theta_2 = \pi V_{\text{DC2}}/V_\pi$ is the optical phase difference between the arms of bottom sub-MZM. V_{RF} and V_{LO} are the amplitudes of the RF and LO signals, respectively. V_π is the half-wave voltage of the DPMZM. When $\theta_1 = \theta_2 = \pi$, both of the two sub-MZMs are biased at the minimum transmission point to achieve the CS-DSB modulation. Then the output of the DPMZM can be expressed as

$$E_{DPMZM}(t) = -\frac{1}{2}\sqrt{P_0}e^{j\omega_0 t}\left[\sin(m_{RF}\cos\omega_{RF}t) + \sin(m_{LO}\cos\omega_{LO}t)e^{j\theta_3}\right] \tag{3}$$

where $\theta_3 = \pi V_{DC3}/V_\pi$ is the optical phase difference between the arms of parent MZM, namely, the optical phase difference between the RF and LO sidebands. Based on the Jacobi-Anger expansion [26], the optical signal can be expanded as

$$E_{DPMZM}(t) = \frac{1}{2}\sqrt{P_0}e^{j\omega_0 t}\begin{bmatrix} \sum_{n=1}^{\infty}(-1)^n J_{2n-1}(m_{RF})(e^{j(2n-1)\omega_{RF}t} + e^{-j(2n-1)\omega_{RF}t}) \\ +\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(m_{LO})(e^{j(2n-1)\omega_{LO}t} + e^{-j(2n-1)\omega_{LO}t})\cdot e^{j\theta_3} \end{bmatrix} \tag{4}$$

where $J_n(\boldsymbol{.})$ is the Bessel function of the first kind of order n. Both of the $\pm$1st order sidebands of the RF and LO signals can generate the interested downconversion frequency signal, whereas only +1st or −1st order sidebands should be left to achieve phase shift. Therefore, an OBPF is adopted to retain the +1st order sidebands. The output of the OBPF can be written as

$$E_{OBPF}(t) = -\frac{1}{2}\sqrt{P_0}\left[J_1(m_{RF})e^{j(\omega_0+\omega_{RF})t} + J_1(m_{LO})e^{j(\omega_0+\omega_{LO})t}e^{j\theta_3}\right] \tag{5}$$

The output optical signals of the OBPF beat at the PD to perform optical-to-electrical conversion. The downconversion signal with the frequency $\omega_{IF} = \omega_{RF} - \omega_{LO}$ is detected and the output photocurrent of PD is

$$i_{IF}(t) = \frac{1}{2}\Re P_0 J_1(m_{RF})J_1(m_{LO})\cos[(\omega_{RF} - \omega_{LO})t - \theta_3] \tag{6}$$

where $\Re$ is the responsivity of the PD. The output power and phase of the IF signal can be obtained from (6) and are given by

$$P_{IF} = \frac{1}{8}\Re^2 P_0^2 J_1^2(m_{RF})J_1^2(m_{LO})R_{out} \tag{7}$$

$$\theta_{IF} = \theta_3 = \pi\frac{V_{DC3}}{V_\pi} \tag{8}$$

where R_{out} is the load resistance of the PD. As can be seen from (7) and (8), the RF signal can be downconverted to IF signal. Furthermore, the phase shift of the IF signal is linear with V_{DC3}, while the power of the IF signal remains unchanged. It is theoretically proved that our system can implement frequency downconversion and phase shifting for RF signal simultaneously.

3. Experimental Results

The experimental setup of all-optical microwave photonic downconverter with phase shifting is illustrated in Fig. 2. The optical carrier is supplied by a distributed feedback-based (DFB) laser with a center wavelength of 1550.09 nm. The output power of laser is 12 dBm. The optical carrier is injected into a commercial single-drive DPMZM (Fujitsu, FTM7962EP). In this modulator, the optical carrier is split equally into two sub-MZMs. The half-wave voltage and 3 dB bandwidth of the DPMZM are 3.5 V and 22 GHz, respectively. The RF signal produced by an analog signal generator (Agilent, E8257D) drives the top sub-MZM of the DPMZM. The LO signal provided by another analog signal generator (R&S, SMB100A) is input to the bottom sub-MZM of the DPMZM. The power of the RF and LO signals are 10 dBm and 14 dBm, respectively. The frequency of the RF and LO signals are 8 GHz and 7 GHz. In order to achieve the CS-DSB modulation, two sub-MZMs in the DPMZM are biased at the minimum transmission point, and the bias voltages V_{DC1} and V_{DC2} are tuned to 5.6 V and 8.9 V, respectively. The CS-DSB modulation optical signals of the RF and LO are obtained from the DPMZM. An OBPF with a sharp roll-off at the filter edges is used to filter out +1st order

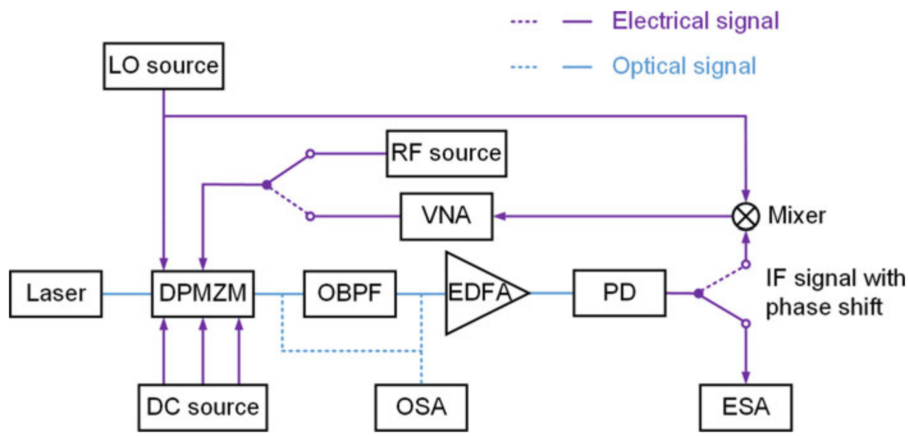

Fig. 2. Experimental setup of the proposed microwave photonic link.

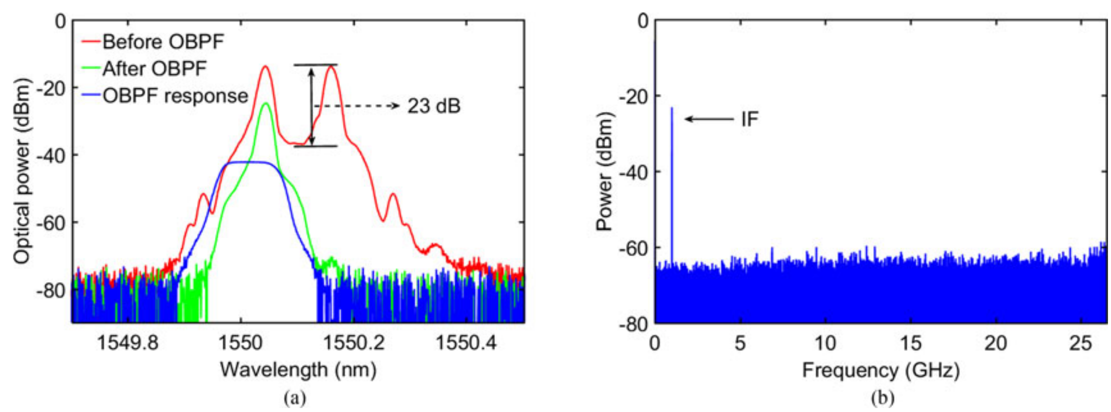

Fig. 3. Measured (a) optical and (b) electrical spectrums of the proposed microwave photonic link.

sidebands of the RF and LO optical signals. Here, the CS-SSB modulation is actually achieved to prepare for the operation of phase shift. After the OBPF, an erbium-doped fiber amplifier (EDFA) which works at automatic power control (APC) mode is applied to compensate the insertion loss of the DPMZM and OBPF. The output optical power of the EDFA is 2.6 dBm. The optical signal is sent to a PD (Conquer, KG-PT-40G) to implement optical-to-electrical conversion. The bandwidth and responsivity of the PD are 40 GHz and 0.65 A/W, respectively.

The optical spectrum before and after the OBPF are measured by using an optical spectrum analyzer (OSA, Yokogawa, AQ6370C). A broadband laser source is used to acquire the response of the OBPF. The optical spectrums are shown in Fig. 3(a). The red line is the CS-DSB modulation optical signal, and it is worth nothing that the $+1$st order RF and LO optical signals cannot be distinguished because the frequency difference between RF and LO is only 1 GHz. The power ratio of the $+1$st order LO optical signal sideband to optical carrier is 23 dB. The blue line is the response of the OBPF, and the green line is the optical signal after the OBPF. We can see that the useless optical carrier and sidebands are suppressed under the noise floor. Then very pure $+1$st order RF and LO optical signals are obtained, which have contributed to optimize the system performance accordingly. Fig. 3(b) is the electrical spectrum of IF signal with a frequency of 1 GHz. It can be seen that the downconverted IF signal will not be interfered by the other uninterested mixing spurs. No additional low-pass electrical filter after PD is needed to remove unwanted signals, and the extraction of IF signal becomes more convenient for the post-processing [11].

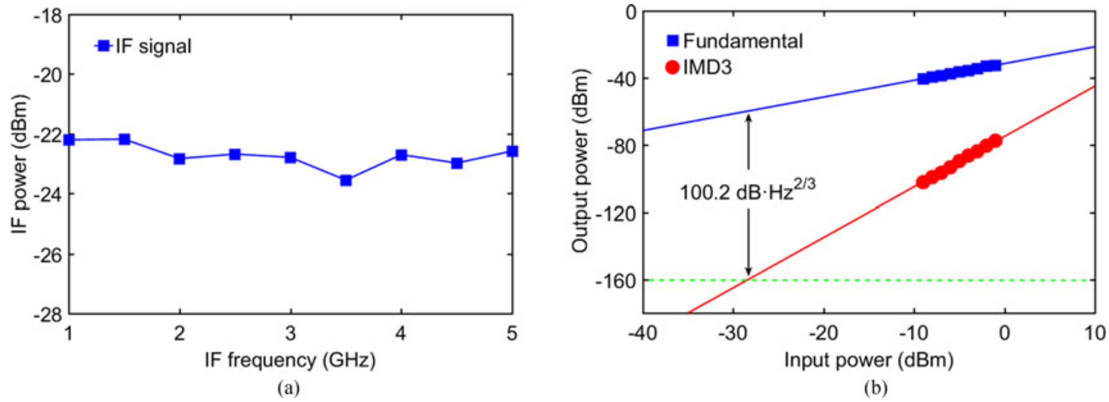

Fig. 4. Measured (a) output power and (b) $SFDR_3$ of the proposed microwave photonic link.

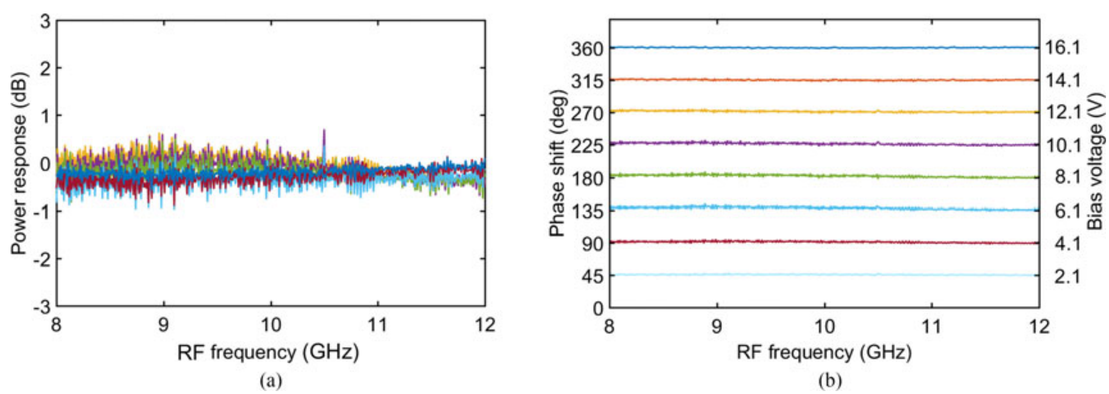

Fig. 5. The phase shift (a) and power response (b) of the proposed microwave photonic link.

The power response of the proposed frequency downconverter is firstly evaluated, using an electrical spectrum analyzer (ESA, Tektronix, RSA5126B). The result is shown in Fig. 4(a). As can be seen, the RF signal is successfully downconverted to the IF signal from 8−12 GHz to 1−5 GHz where the LO frequency is 7 GHz and the power fluctuation of the converted IF signal is below 0.41 dB. The SFDR is an important performance parameter of microwave photonic downconverter. And it is the power ratio of the fundamental signal to the nth-order intermodulation distortion (IMDn) when the power of IMDn is equal to the noise floor. For the downconverter, the IMD3 is the primary Interference signal, thus $SFDR_3$ is usually used to evaluate the system performance. A two-tone microwave signal at 8 and 8.1 GHz is fed to the DPMZM to test the $SFDR_3$ of system. The frequencies of IF signals are 1.0 and 1.1 GHz, respectively. The powers of the fundamental signal and the third-order intermodulation distortion (IMD3) signal are detected experimentally. The result is depicted in Fig. 4(b), and shows that the $SFDR_3$ is 100.2 dB·$Hz^{2/3}$.

To test the phase shifting of the IF signal, seen from Fig. 2, a two-port vector network analyzer (VNA, R&S, ZNB40) is used to replace the analog signal generator to output the RF signal. The power of the RF signal from VNA is 10 dBm, and the frequency is swept from 8 to 12 GHz with an interval of 10 MHz. The bandwidth of the IF signal is 1 to 5 GHz where the frequency of the LO signal is also fixed at 7 GHz. An electrical mixer (Marki Microwave, T3H-20) is used to upconvert the IF signal to the RF signal by the same LO signal, and then the recovered RF signal is input to the VNA. By tuning the DC3 voltage of the DPMZM, the phase of the IF signal is continuously changed. It can be seen from Fig. 5(a) that the phase shift over full range from 0° to 360° has been achieved for the IF signal with a bandwidth of 4 GHz. It is worth noting that the test bandwidth is limited by

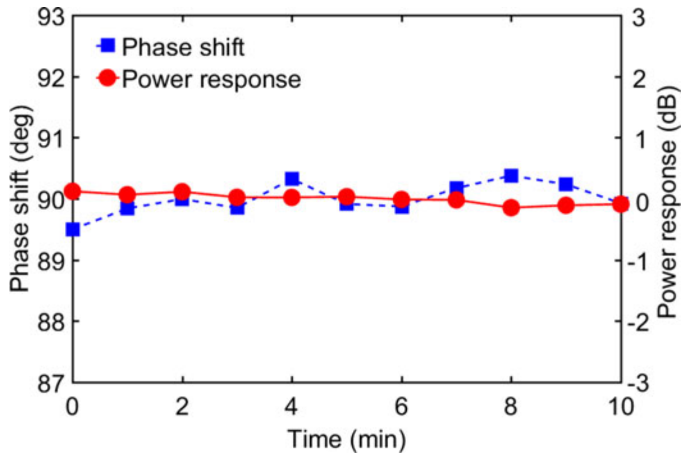

Fig. 6. The stability of the phase shift of the proposed microwave photonic link.

electrical mixer. Actually, the bandwidth of proposed system is only determined by DPMZM. The voltage difference of 16.1 V corresponds to a phase shift of 360°. The phase deviation is within 2°, which illustrates that the proposed microwave photonic link possesses good accuracy of phase shift for the wideband RF signal. Besides, the power response of the IF signal with phase shift is also obtained as shown in Fig. 5(b). The deviation of the IF power is less than 0.26 dB, which is almost uncorrelated with phase shift. The phase shift of IF signal varies linearly with the DC bias voltage of parent MZM (about 2V corresponding to 45°), which is in good agreement with the theoretical analysis.

The phase stability of proposed system is also analyzed for the frequency and phase shift of the RF signal at 12 GHz and 90°, respectively. As can be seen in Fig. 6, the phase drift is within 0.5° and the power ripple is less than 0.2 dB in 10 minutes. It indicates that proposed system has a good stability for phase shift.

4. Conclusion

An all-optical microwave photonic downconverter with tunable phase shift based on a single-drive DPMZM and an OBPF is theoretically analyzed and experimentally demonstrated. The RF and LO signals drive the top and bottom sub-MZMs in the DPMZM, respectively. The CS-DSB modulation is performed by controlling the DC voltages of two sub-MZMs. A very pure +1st order RF and LO optical signals are obtained by the OBPF, and the IF signal is produced by a PD. The IF power is substantially retained at different RF frequencies, where the $SFDR_3$ of the system is 100.2 $dB\cdot Hz^{2/3}$. By adjusting the bias voltage of parent MZM in the DPMZM, the continuous and linear phase shift of the IF signal is achieved from 0° to 360°. The phase deviation and power ripple of the IF signal are less than 2° and 0.26 dB, respectively, meanwhile, the stability is also good enough. Considering that no electrical component is used, the system has the characteristic of wide bandwidth. Furthermore, since the microwave photonic link can simultaneously fullfill frequency downconversion and phase shift, it is expected to simplify the setup design and reduce the cost of the phased-array beamforming, high-speed signal processing and RoF system.

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