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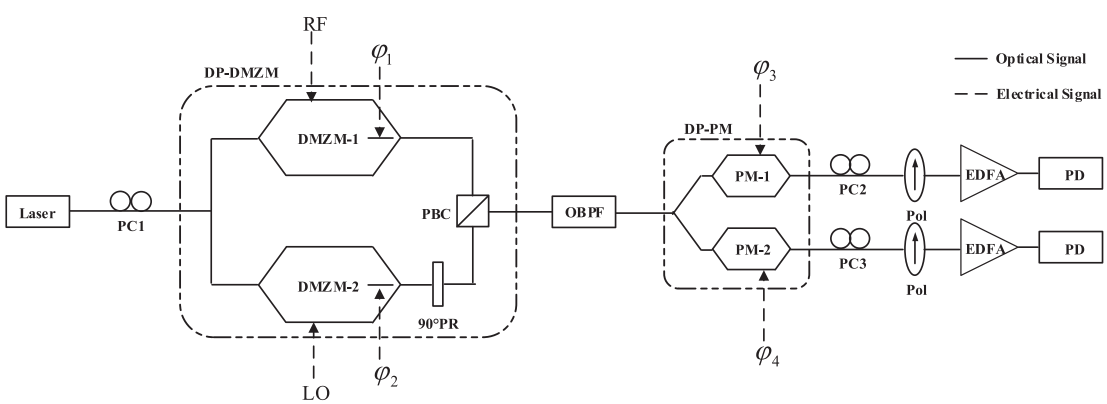

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Dual-Channel Phase-Tunable Down Converter With LO Frequency Doubling

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Abstract: A dual-channel phase-tunable down converter with local oscillator (LO) frequency doubling is proposed by using a commercial dual-polarization dual-drive Mach-Zehnder modulator (DP-DMZM) and a specially designed dual-channel phase modulator (DP-PM). A radio frequency (RF) signal is injected to one of sub-DMZMs in the DP-DMZM, and a LO signal modulates another sub-DPMZM. An optical bandpass filter (OBPF) is used to filter out the unwanted sidebands, and only the +2nd-order LO and +1st-order RF sidebands are remained and output to the DP-PM. The DP-PM is composed by two parallel PMs with different modulation efficiency between orthogonal polarizations. Each bias voltage of the DP-PM can linearly vary the phase shift between the RF and LO modulated optical sidebands. After detected by a photodetector, the down converted signal with doubled LO frequency and dual-channel phase shift can be obtained. The principle of the proposed link is verified and the experiments are carried out. The experimental results show that the average spur suppression ratio of the down-converted signals is 29.15 dB. The spurious-free dynamic range (SFDR) of the down converter is 103.94 dB·Hz$^{2/3}$. The continuous and dependent dual-channel phase shift with the full range of 360° can be experimentally achieved. The proposed down converter integrates multiple function in a link, and has the merit of high electrical purity and convenient operation.

Index Terms: Microwave photonics, down converter, dual-channel phase shift, frequency doubling.

1. Introduction

Frequency conversion and tunable phase shift are two significant functions in the modern communication transmitter and receiver. With the rapid development of modern communication, the high operating frequency and large bandwidth are urgently demanded. Conventional microwave technique suffers from narrow operation bandwidth, low isolation and serious distortion [1]–[5]. To break through these issues, microwave photonics technique has been presented, which is inherently characterized by low transmission loss, wide bandwidth and resistance to electromagnetic interference. Various photonics-assisted microwave frequency converters and phase shifters have been investigated and applied in phased-array radar, broadband wireless communication, electronic warfare and deep space exploration [6]–[9]. Microwave photonics has been demonstrated as an effective method to meet the requirement of modern communication system.

The wideband phase shifter is an essential component for phase-coded radar system and phase arrayed beamforming networks [10]–[13]. Many researches have been reported in recent years [14]–[21]. Microwave photonic phase shifter is proposed based on a dual-parallel Mach-Zehnder modulator (DPMZM) [14] or a dual-polarization dual-drive MZM (DP-DMZM) [15]. In these methods, the bias voltage of the sub-MZM is tuned to realize 360° phase shifting. However, it is difficult to implement the multichannel phase shifting to satisfy the practical applications like phased-array radar system. In order to achieve the multichannel phase shifting, a polarization controller (PC) and a polarizer (Pol) are combined to introduce the optical phase in each channel [16]. Several pairs of the PC and Pol make the system quite complex, and the accuracy of multichannel phase shifter is determined by the rotation precision and consistency of the discrete PCs. Besides, multichannel discrete phase modulators (PMs) are also applied to the phase shifting of microwave signals [17]. Owing to the polarization sensitivity of modulator, different phase shift is generated for diverse polarizations. It is a feasible and effective solution to realize the phase shifting. Nevertheless, multiple discrete components lead to complex structure, instability and inconsistency to some extent. The multichannel phase shifters above is theoretical verified, however only one single channel phase shifter is demonstrated experimentally. In addition, optical nonlinear effect, such as semiconductor optical amplifier (SOA) [18], [19] or Brillouin frequency shift (SBS) [20], [21], has also been applied for microwave photonic phase shift. In the SOA-based phase shifter, an optical filter is applied to increase the effect of the red-shifted or blue-shifted to produce the microwave phase shift. In the SBS-based method, phase shift can be introduced by the interaction of several waves in optical fiber. However, these phase shifters often suffer from extra spurious or complex structure, and it is difficult to achieve multi-channel phase shift.

Microwave conversion, including up-conversion and down-conversion, is also a vital function in the transmitter and receiver for many communication systems. With the active demand of high-frequency band, the work frequency of modern microwave communication system has been greatly promoted even to the millimeter wave. In order to detect the microwave signal with a higher frequency, the local oscillator (LO) frequency has to be further enhanced, resulting in high cost and sometimes unfeasibility due to the electronic bottleneck problem. Fortunately, microwave photonics link (MPL) processes the microwave signal in optical domain, which supplies the possibility to realize high-frequency mixing with a low-frequency LO. The high-order modulation sidebands of the LO signal could be chosen for high-frequency conversion to substitute for the high-frequency LO. A microwave photonic I/Q up-converter has been presented [22], in which the bias voltages of modulator are adjusted to obtain the I/Q modulation with low-frequency LO signal. A LO doubling-based mixer is reported by using a DPMZM [23] or a DP-DPMZM [24]. The sub-MZMs in their links are both operated at the maximum transfer points to get the 2nd-order LO optical sidebands. Besides, three MZMs are cascaded to achieve the up-conversion with frequency quadrupling [25]. However, the unwanted optical sidebands are not well suppressed, and many harmonic mixing spurs are produced during the frequency beating. Therefore, the quality of converted signal will be greatly deteriorated and extra filters have to be utilized.

Thanks to the flexibility of microwave photonics, the phase shift and the frequency conversion has been realized simultaneously in a single MPL. A up-conversion link with LO frequency doubling and phase shift is implemented by a MZM cascaded with a DPMZM [26]. Down-converter [27] and mixer [28] with frequency doubled LO and phase shift are achieved by a DP-DPMZM. Moreover, a photonic-assisted microwave hybrid combiner is also designed by a DP-DPMZM and an optical bandpass filter (OBPF) [29]. In this link, the phase shift and power ratio of the microwave signals can be tuned continuously and flexibly. In above approaches, the sub-harmonic sideband of LO signal and the adjustment of bias voltage of modulator are used to realize the frequency doubling and tunable phase shifting, respectively. However, the cascaded structure of the MZM and DPMZM is not suitable for the multichannel microwave system.

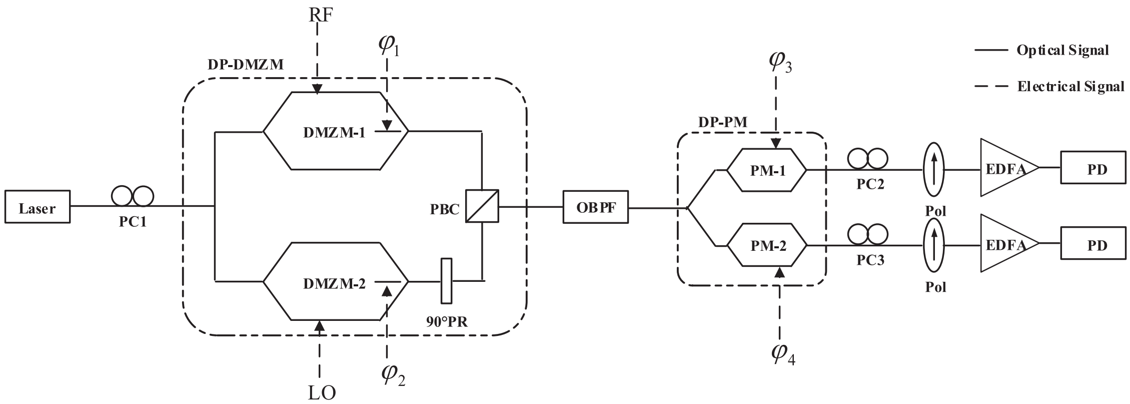


Fig. 1. The structure of the proposed dual-channel down conversion link.

In this paper, a dual-channel phase-tunable down converter with LO frequency doubling is proposed by a commercial DP-DMZM and a specially designed dual-parallel phase modulator (DP-PM). The RF signal modulates one of the sub-DMZMs; meanwhile, the LO signal is injected to another sub-DMZM. The two sub-DMZMs work at quarter points. An OBPF is applied to remove the useless sidebands, and only the +2nd-order LO sideband and the +1st-order RF sideband are primarily left. The integrated DP-PM has the feature of polarization sensitivity, leading to different modulation efficiency between orthogonal polarizations. The dual-channel phase shift is realized simultaneously by varying two bias voltages of the DP-PM. The down-conversion signal with continuously regulated phase shift is able to be obtained by the photo-electric conversion at the photodetector (PD). The principle of the proposed down-converter is analyzed, and the experiments are implemented. The experimental results show that the proposed link can fulfil arbitrarily tunable 360° phase shift for two channels. The suppression ratio of the down conversion signal averagely reaches 29.15 dB, and the performance of spurious-free dynamic range (SFDR) is measured at 103.94 dB·Hz$^{2/3}$.

2. Principle

The structure of the presented two-channel phase-tunable down converter with doubled LO frequency is shown in Fig. 1. The optical carrier is generated from a laser source and is sent to a DP-DMZM. The DP-DMZM is a commercial modulator with two sub-DMZMs (DMZM-1 and DMZM-2) integrated in parallel structure. A 90° polarization rotator (PR) is lying in the lower branch of DP-DMZM. The output of sub-DMZMs are combined by a polarization combiner (PBC). The RF signal is introduced to the DMZM-1, while the LO signal modulates the DMZM-2. Due to the PR, the optical field from the DP-DMZM contains two signals in orthogonal polarization directions. The unwanted sidebands are removed out by an optical bandpass filter. Then the output signal is injected to a specially designed DP-PM, which has difference modulation efficiency between orthogonal polarizations. Because of the different modulation efficiency, the introduced phases of RF and LO signals are distinct at the same DC voltage. For the sake of tuning the orthogonal polarizations to the linear one before frequency beating, the output signal of the DP-PM is fed to the PCs and polarizers. After amplifying by an erbium-doped fiber amplifiers (EDFA), the output signal is injected to photodetectors, afterwards the dual-channel down-conversion signals with doubled LO frequency and phase shift can be obtained.

Then, the principle of proposed down-conversion and phase shift link is analyzed. The output of DMZM-1 can be written as

$$E_{DMZM-1} = E_0 \exp(j\omega_0 t) \exp(j\varphi_1) \exp\left[j\beta_{RF} \cos(\omega_{RF} t)\right] \tag{1}$$

where ω_0 and E_0 are the angular frequency and amplitude of the optical carrier. φ_m ($m = 1, 2$) is the phase shift introduced by the DC bias voltage $V_{\rm m}$ of the DP-DMZM. In this MPL, the φ_1 and φ_2 are set to be $\pi/4$. The $\omega_{\rm RF}$ and β_{RF} are the angular frequency and modulation index of RF signal. After the Bessel function expansion, Eq. (1) can be described as

$$E_{DMZM-1} = \frac{\sqrt{2}}{2} E_0 \exp(j\omega_0 t) \sum_{n=-\infty}^{\infty} i^n J_n(\beta_{RF}) \exp(jn\omega_{RF} t) \tag{2}$$

where $J_n(.)$ is the nth-order first kind Bessel function. Similarly, the output of the DMZM-2 can be written as

$$E_{DMZM-2} = \frac{\sqrt{2}}{2} E_0 \exp(j\omega_0 t) \exp\left[j\beta_{LO} \cos(\omega_{LO} t)\right] \tag{3}$$

where the β_{LO} and ω_{LO} are the modulation index and angular frequency of the LO signal. The output optical signal with Bessel function expansion can be expressed as

$$E_{DMZM-2} = \frac{\sqrt{2}}{2} E_0 \exp(j\omega_0 t) \sum_{n=-\infty}^{\infty} i^n J_n(\beta_{LO}) \exp(jn\omega_{LO} t) \tag{4}$$

An integrated 90° PR in the DP-DMZM is applied to change the polarization direction, so the upper and lower output signals have orthogonal polarization states. The output optical field of the DP-DMZM can be denoted as

$$E_{DP-DMZM} = \begin{bmatrix} E_{DMZM-1} \\ E_{DMZM-2} \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{2}}{2} E_0 \exp(j\omega_0 t) \sum\limits_{n=-\infty}^{\infty} i^n J_n(\beta_{RF}) \exp(jn\omega_{RF} t) \\ \frac{\sqrt{2}}{2} E_0 \exp(j\omega_0 t) \sum\limits_{n=-\infty}^{\infty} i^n J_n(\beta_{LO}) \exp(jn\omega_{LO} t) \end{bmatrix} \tag{5}$$

Next, an OBPF is utilized to suppress the useless optical signal sidebands and optical carrier. Only the $+$2nd-order LO and the $+$1st-order RF modulation sidebands are maintained. The output of the DP-DMZM can be described as

$$E_{DP-DMZM} = \begin{bmatrix} E_{DMZM-1} \\ E_{DMZM-2} \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{2}}{2} E_0 \exp(j\omega_0 t) J_1(\beta_{RF}) \exp(j\omega_{RF} t) \\ \frac{\sqrt{2}}{2} E_0 \exp(j\omega_0 t) J_2(\beta_{LO}) \exp(j2\omega_{LO} t) \end{bmatrix} \tag{6}$$

The tunable phase shift is achieved by using an integrated polarization sensitivity dual-parallel PM. Due to the diverse modulation efficiency between orthogonal polarizations, the phase shifts of the RF and LO modulation sidebands are distinct by turning the DC bias voltages of DP-PM. Taking the first channel as an example, the output of the DP-PM can be expressed as

$$E_{PM-1} = \begin{bmatrix} E_{DMZM-1} \\ E_{DMZM-2} \end{bmatrix} \cdot \begin{bmatrix} \exp(j\varphi_{3,TM}) & 0 \\ 0 & \exp(j\varphi_{3,TE}) \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{2}}{2} E_0 \exp(j\omega_0 t) J_1(\beta_{RF}) \exp(j(\omega_{RF} t + \varphi_{3,TM})) \\ \frac{\sqrt{2}}{2} E_0 \exp(j\omega_0 t) J_2(\beta_{LO}) \exp(j(2\omega_{LO} t + \varphi_{3,TE})) \end{bmatrix} \tag{7}$$

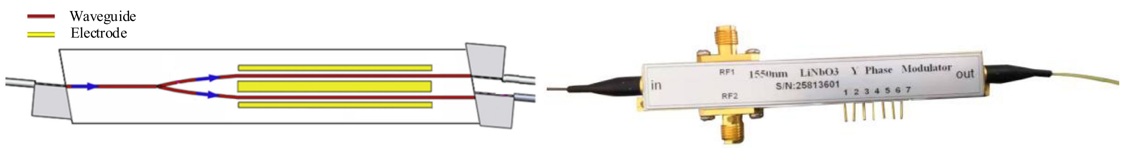
where $\varphi_{3,TM}$ and $\varphi_{3,TE}$ are the phase shift controlled by the DC bias voltage of the DP-PM in TM and TE polarizations. In order to project to the linear polarization state, the optical signal is injected to a PC and a polarizer with 45°. The output of the Pol can be described as

$$E_{\rm Pol} = \frac{\sqrt{2}}{2} E_{DMZM-1} \exp(j\varphi_{3,TM}) + \frac{\sqrt{2}}{2} E_{DMZM-2} \exp(j\varphi_{3,TE}) \tag{8}$$

Then the output optical signal after the Pol is sent to a PD for frequency beating, and the output photocurrent of the PD can be denoted as

$$I(t) = E_{Pol} \cdot E_{Pol}{}^{*} \propto \Re E_0{}^2 J_1(\beta_{RF}) J_2(\beta_{LO}) \cos\left[(2\omega_{LO} - \omega_{RF})t + (\varphi_{3,TE} - \varphi_{3,TM})\right] \tag{9}$$

where $\Re$ is the responsivity of photodetector.



(a) (b)

Fig. 2. Dual-channel phase modulator: (a) Internal structure diagram; (b) Photo.

It can be distinctly seen that the down conversion signal with frequency of $2\omega_{\mathrm{LO}}$-ω_{RF} could be acquired. The phase shifts of the dual-channel down conversion signal can be continuously and dependently varied by the DC bias voltages of DP-PM. The phase of down conversion signal changes linearly with respect to the DC bias voltages of DP-PM, while the amplitude of the down-converted signal is not varied.

In summary, the presented microwave photonic link can simultaneously achieve down conversion, doubled LO frequency and dual-channel phase shifting. Since only the DC bias voltage of the DP-PM demands to be adjusted for the phase shift, the operation and structure of the MPL is much simpler compared with most of the reported methods. Furthermore, profiting from the integrated DP-PM, a dual-channel phase shifting can be achieved for the dual-channel down-converted microwave signals with high reliability and stability.

3. Results

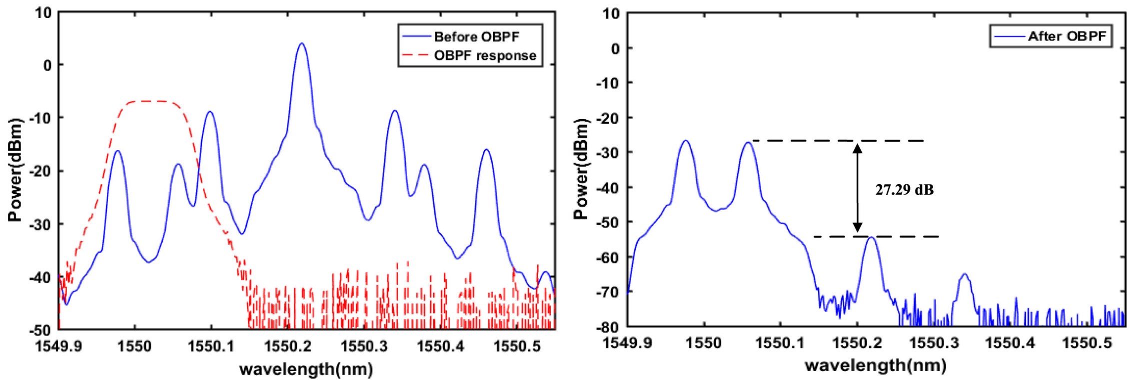
The experimental MPL of the down conversion with LO frequency doubling and dual-channel phase shift is carried out according to Fig. 1. A distributed feedback-based (DFB) laser generates the light wave with the center wavelength of 1550.21 nm and the power of 16 dBm. The output light wave is sent to a commercial DP-DMZM (Fujitsu FTM7980HQA). The half-wave voltage of DP-DMZM is 3.5 V and the bandwidth of DP-DMZM is 23 GHz. The RF and LO signals are supplied by two microwave signal generators (ROHDE&SCHWARZ SMB100A). The RF signal is launched to the DMZM-1, meanwhile, the LO signal is introduced to the DMZM-2. Because of the PR in the DP-DMZM, the output polarization directions from the DMZM-1 and DMZM-2 are maintained in orthogonal. Then only the $+1$st-order sideband of RF signal and the $+2$nd-order sideband of LO signal are remained by an OBPF. The output of OBPF is sent to the DP-PM for phase shift. Afterwards the output signal of the DP-PM is injected to two PCs and two polarizers. EDFAs are applied to compensate the link loss. Finally, the output optical signals are fed to two PDs (FINISAR, XPDV2120R, 50 GHz, 0.65 A/W) to obtain the down-conversion signals with phase shift.

The $LiNbO_3$ DP-PM is fabricated by Ti-diffusion process, which can ensure the modulation of the light wave with both TE and TM modes. The internal structure and photo of the DP-PM is shown in Fig. 2. The input light wave is divided into two arms via a Y waveguide, and the modulation is realized by sharing a ground electrode. The DP-PM has the half wave voltage of 4.5 V for the TM polarization. For a $LiNbO_3$ electro-optic DP-PM, the modulation efficiency in TM polarization is about 3 times as in TE polarization [30]. Hence the difference between the optical phases of the TM and TE modes is varied linearly related to the DC voltage of DP-PM as

$$\varphi_{TM} - \varphi_{TE} = \frac{2\pi V_{DC}}{3V_{\pi,PM}} \tag{10}$$

where φ_{TM} and φ_{TE} are the phase shift introduced by the DC voltages of DP-PM in TE and TM polarizations, $V_{\pi,PM}$ is the half-wave voltage of the DP-PM for TM polarization.

Firstly, optical spectrums are analyzed by an optical spectrum analyzer (OSA, Yokogawa, AQ6370C) with 0.02 nm resolution to test the modulation performance of the RF and LO signals. In the experiments, the frequency of the LO signal is 15 GHz and the power is 18 dBm. The frequency



(a) (b)

Fig. 3. The output optical spectrums after (a) DP-DMZM and (b) OBPF.

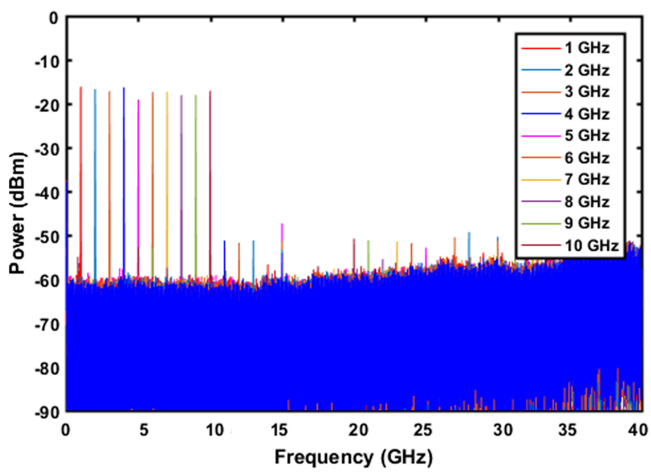


Fig. 4. The output electric spectrum after PD with IF signals from 1 GHz to 10 GHz.

and power of RF signal is set to be 20 GHz and 11 dBm. The output spectrums from DP-DMZM are shown in Fig. 3(a). It can be found that there are multistage sidebands of LO and RF due to the nonlinear modulation effect. The OBPF is introduced to filter the unwanted sidebands out, and only the +2nd-order LO and +1st-order RF sidebands are maintained and are sent to the DP-PM modulator. The power of the +2nd-order LO and +1st-order RF sidebands are −27.24 dBm and −27.67 dBm as indicated in Fig. 3(b). The power ratio between the RF signal and optical carrier is 27.29 dB. It can be seen that the purity of optical spectrums is high after the OBPF.

Then, the purity of electric spectrum is also tested with the same experiment condition. The down-conversion signals are measured by an electric spectrum analyzer (ESA, Keysight N9041B). With RF signal changed from 20 GHz to 29 GHz, the down-conversion IF signals from 10 GHz to 1 GHz can be obtained after the PD. The spectrums of down-conversion IF signals are illustrated in Fig. 4 with the RBW of 3 MHz. Owing to the high suppression ratio of unwanted sidebands, the purity of electrical signal is maintained in high performance. The average ratio between spur signals and IF signal reaches 29.15 dB.

SFDR is one of significant evaluation parameters for the microwave photonic converter. SFDR is defined as the ratio between the fundamental and the distortion signal when the output power of distortion signal is just over the noise floor. Generally, the third-order distortion is the most

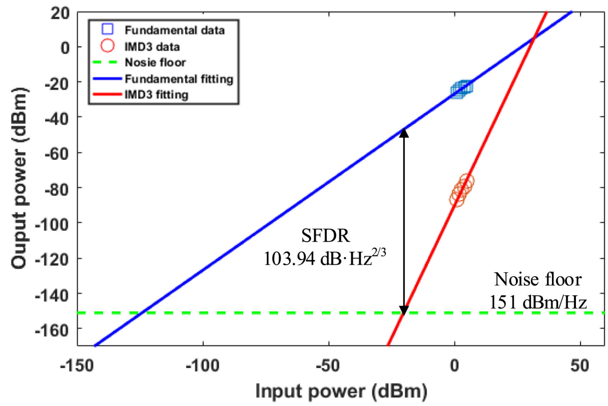


Fig. 5. The SFDR of the proposed down conversion link.

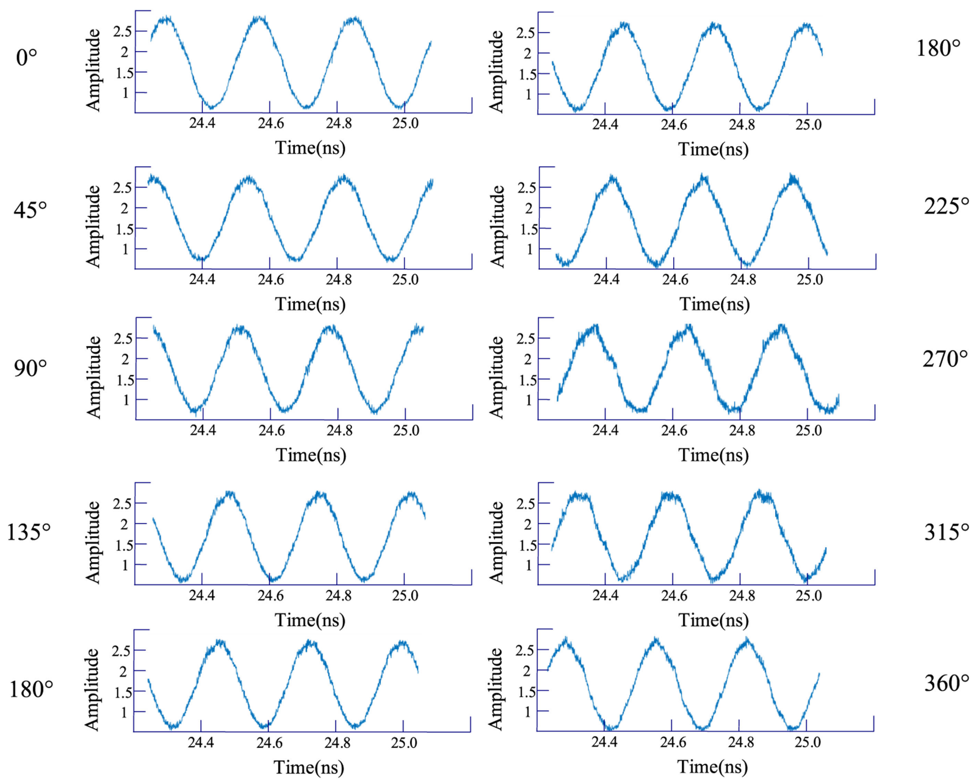


Fig. 6. Phase shift of the down conversion signal from 0° to 360° via changing the V_3.

serious distortion in MPL. The two-tone RF signal at 23.9 and 24 GHz is applied to measure the SFDR of the down converter. The frequency of LO signal is set to be 15 GHz and its power is 19 dBm. The frequencies of the down-converted fundamental signals are 6 GHz and 6.1 GHz, so the frequencies of IMD3 signals in this link should be 5.9 GHz and 6.2 GHz correspondingly. The IMD3 and fundamental signals are also measured by the ESA, and the results of output power are shown in Fig. 5. It can be seen that the SFDR of proposed link is 103.94 dB·$Hz^{2/3}$.

Next, the ability of phase shift in one channel is demonstrated. In order to test the phase-shift performance at high frequency, the optical oscilloscope (Agilent, 86100C) with 40 GHz input bandwidth is applied to record the waveform of the down conversion signal. The frequency of

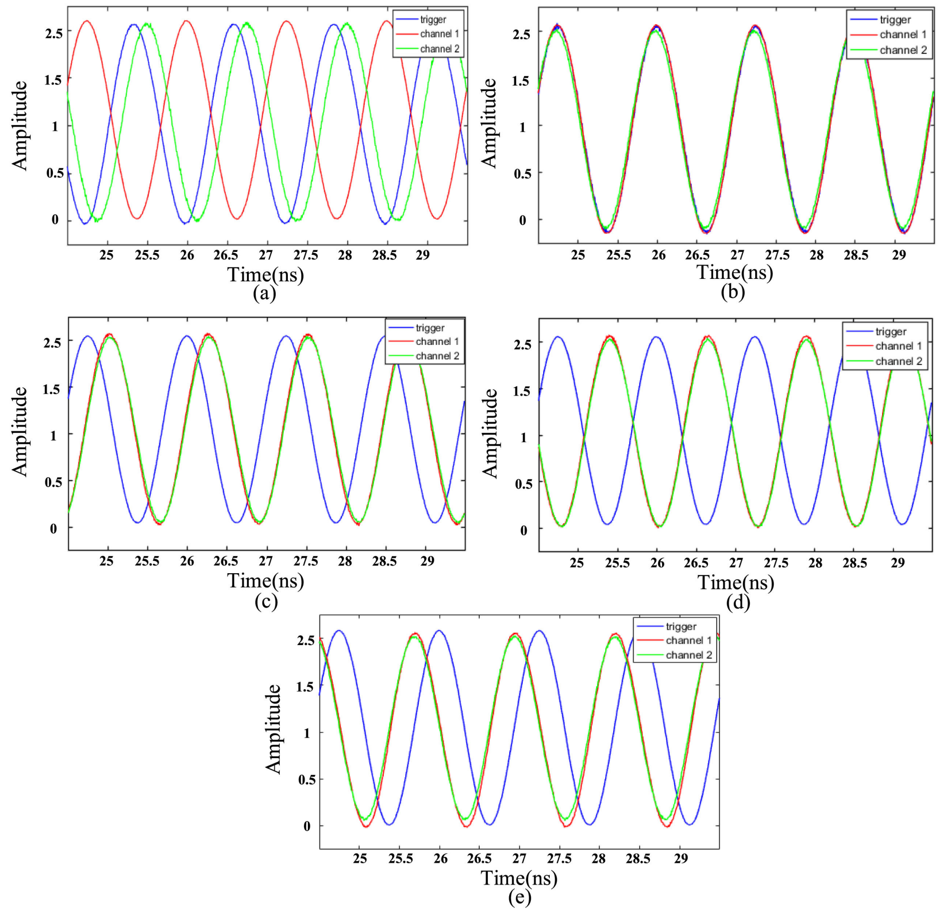


Fig. 7. Phase shift of the two channels down conversion signal in (a) the Initial state, (b) in phase, (c) 90°, (d) 180°, and (e) 270°.

the RF signal is set to be 25 GHz, meanwhile, the LO frequency is 15 GHz. In this case, the down conversion signal at 5 GHz is acquired by the oscilloscope. The phase shift of the down conversion signal is adjusted by the bias voltage V_3 of DP-PM. Waveforms of the down conversion signals are shown in Fig. 6. It can be observed that one-channel phase shift is obtained with a full range of 360°. The phase shift of down conversion signal varies linearly by the bias voltage of V_3, and V_3 needs to be changed about 1.27 V for the phase shift of 45°.

Finally, the capability of dual-channel phase shift is carried out. Another multichannel oscilloscope is applied to measure the waveforms of the two-channel down conversion signals. This oscilloscope has four electrical channels with 1 GHz input bandwidth. The frequencies of the LO and RF signals are set to be 15 GHz and 29.5 GHz, and the two down conversion signals are both at 0.5 GHz after two PDs. A trigger signal from microwave signal generator is introduced as a standard reference signal, and we define that the initial phase of trigger signal is 0°. Figure 7 shows the waveforms of trigger signal and two-channel down conversion signals. During the fabrication of the DP-PM, the waveguide length of parallel sub-PMs is difficult to be completely consistent. Therefore, the initial phase of the two channels may be different at the same bias voltage. Here, the bias voltages of V_3 and V_4 are both set to be 0 V, and we can see that an inherent phase difference between two signals exists as shown in Fig. 7(a). Then the bias voltage of V_3 and V_4 are turned to be 2.50 V and 4.03 V, and all the phases of those signal are shifted to be 0° as depicted in Fig. 7(b). With the bias voltages of V_3 and V_4 changing to be 3.38 V and 3.29 V, the two-channel down-converted signals with the phase shift of 90° can be obtained as shown in

Fig. 7(c). Then the bias voltages continue to turn to 4.48 V and 2.80 V, and the 180° phase shift in the two channels can be measured as indicated in Fig. 6(d). Finally, the bias voltages of V_3 and V_4 are set to be 6.78 V and 1.19 V, the phase shift of 270° can be achieved as shown in Fig. 7(e). The experimental results demonstrate that the phase of the two-channel down-conversion signals can be dependently controlled in parallel. Four or more sub-PMs array in parallel could be further integrated in a $LiNbO_3$ modulator [31]. Besides, it is worth noting that the different noise level of Fig. 6 and Fig. 7 mainly derived from the usage of different oscilloscopes.

4. Conclusion

A dual-channel phase-tunable down converter with LO frequency doubling is presented and proved by using a DP-DMZM and a specially designed DP-PM. One of the sub-DMZMs in the DP-DMZM is modulated by the RF signal; meanwhile, the LO signal is sent to another sub-DMZM. An optical bandpass filter is applied to remove the unwanted optical sidebands, and only the $+1$st-order RF sideband and the $+2$nd-order LO sideband are retained. An integrated polarization sensitivity DP-PM modulator is introduced to accomplish the dual-channel phase shifting of the converted signals by turning the bias voltages. Finally, the down conversion signals with continuous and adjustable phase shift is acquired by the photo-electric conversion at the photodetector. In the experiment, the suppression ratio of the down conversion signal is 29.15 dB and the performance of SFDR is 103.94 dB·$Hz^{2/3}$. The 360° phase shift for single channel has been achieved through changing one bias voltage of the modulator. Furthermore, it is also experimentally proved that the link can control the full range phase shift for two-channel down-conversion signals. The proposed method has the benefit of multiple functions including down conversion, doubled LO frequency and 360° phase shift. Dual-channel phase shifts are introduced by a DP-PM, which is convenient for its integration and simple operation. The DP-PM could be further expanded to more parallel sub-PMs. The proposed link has advantages of high purity and convenient operation, which possesses potential applications as a receiver in the phased array beamforming networks.

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