Pramana – J. Phys. (2018) 91:3
https://doi.org/10.1007/s12043-018-1573-6

Tunable microwave generation based on frequency quadrupling

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MS received 10 April 2017; revised 7 December 2017; accepted 28 December 2017; published online 29 May 2018

Abstract. To generate linearly chirped microwave signals with large frequency tunable range, a photonic approach is proposed. A dual-output dual-parallel Mach–Zehnder modulator followed by a polarisation beam combiner and an optical filter are utilised to generate orthogonally polarised ± second-order optical sidebands. A polarisation modulator is employed to achieve phase modulation of the two wavelengths. The balanced detection is applied to suppress the distortion and background noise. The central frequency of the generated signal is four times that of the local oscillator frequency. Simulation results show that a linear pulse is produced with time-bandwidth as well as a compression ratio for the pulse of 11 and 9.3 respectively. Moreover, a peak-to-sidelobe ratio of 7.4 dB is generated. The system has both good reconfigurability and tunability, and its frequency can be continuously adjusted from about 10 GHz to as much as 50 GHz in principle.

Keywords. Signal processing; microwave photonics; photodetectors.

PACS Nos 42.15.Eq; 42.30.Lr; 42.79.−e; 84.40.Ua

1. Introduction

It is critical for modern radar systems with high resolutions to have the capability of generating chirped microwave or millimeter wave (mm-wave) pulse [1]. Chirped signals are conventionally obtained by using electronic circuits, but with limitations of small bandwidth and low central frequency. But, some radar systems require central frequency as much as tens or even hundreds of GHz [2]. In comparison with electrical circuits, photonic methods have the advantage of large bandwidth, high frequency, wide tunability and low loss in chirped signal generation.

A variety of photonic methods for generating chirped signals have been reported. The direct space-to-time mapping on the basis of spatial light modulator [3] can generate reconfigurable chirped pulse, but the system is bulky, lossy and complicated. Interfering of two dispersed optical pulses [4,5] can achieve a chirped pulse with tunable central frequency, but the systems are sensitive to environmental variations. A chirped pulse can be generated through optical spectral shaping followed by frequency-to-time mapping. However, for the all-fibre-based approaches [6,7], the generated pulses are usually fixed, while for the silicon chip-based approaches [8,9], tunable pulses can be achieved but with a simple signal profile. Recently, self-heterodyning is also proposed to generate a chirped pulse, and the key components are the directly modulated laser diode (LD) and Mach–Zehnder interferometer [10]. However, both the central frequency as well as the bandwidth of the pulse generated cannot be controlled independently. A chirped pulse can also be generated by external phase modulating two phase-correlated wavelengths [11]. The significance of this scheme is that the generated signal has both tunability and reconfigurability. To overcome the stability problem caused by separated optical paths, polarisation modulator (PolM)-based approaches are intensively investigated [12–19]. This method also faces the challenge of the generation of two orthogonally polarised wavelengths. Furthermore, frequency multiplication is needed to improve the signal frequency. For example, the adoption of a Mach–Zehnder modulator (MZM) followed by a differential group delay device [15] or a Mach–Zehnder interferometer followed by a polarisation beam combiner (PBC) can achieve the

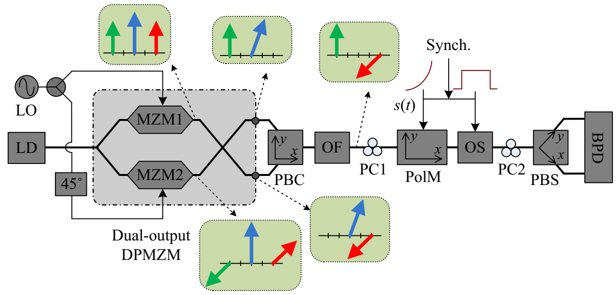

Figure 1. Schematic of the proposed chirped mm-wave pulse generation. LO, local oscillator; LD, laser diode; DPMZM, dual-parallel Mach–Zehnder modulator; PBC, polarisation beam combiner; OF, optical filter; PC, polarisation controller; PolM, polarisation modulator; OS, optical switch; PBS, polarisation beam splitter; BPD, balanced photodetector.

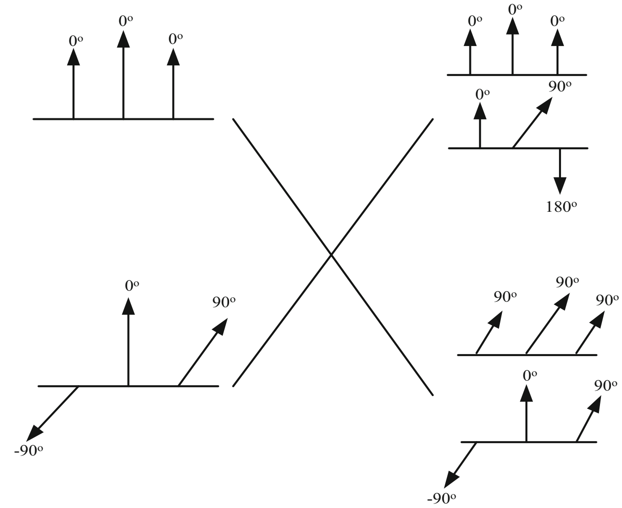

Figure 2. Illustration of the phase transformation.

frequency-doubled orthogonally polarised wavelengths [16]. They also can be generated by using cascaded MZM and PolM combined with an optical filter (OF) [17], or by using dual-parallel PolM [18]. For these approaches, however, the frequency multiplication factor (FMF) is only 2, and a higher FMF is desired to support even higher frequency applications. Frequency-quadrupled orthogonally polarised wavelengths can be generated by using an MZM followed by an OF and a polarisation-maintaining fibre Bragg grating (PM-FBG) [19], but the response of PM-FBG is wavelength-dependent, which makes the tunability of the signal limited.

This paper proposes an innovative photonic scheme for the generation of a linearly chirped pulse. Second-order optical sidebands in the proposed scheme are first produced as two orthogonally polarised phase-correlated wavelengths using a dual-output dual-parallel Mach–Zehnder modulator (DPMZM) followed by a PBC and an OF. Then, a PolM driven by a parabolic signal is applied to the introduction of a parabolic phase deviation to both the optical wavelengths. At last, balanced detection is applied to obtain electrical linearly chirped pulse and suppress the distortion and background noise. The proposal has good reconfigurability and tunability, and it can provide a large and continuous frequency tunable range, more than tens of GHz for the generated linearly chirped signal.

2. Principle

Figure 1 shows how the proposed chirped mm-wave pulse is generated. A dual-output DPMZM, consisting of two sub-MZMs with identical performances placed in parallel and a directional coupler, receives the light sent by an LD. A sinusoidal microwave from the local oscillator (LO) is separated into two paths with a phase gap of 45° and applied to both the sub-MZMs (MZM1 as well as MZM2). Both the MZMs are arranged to be biased at the maximum point for transmission (MATP) so that the optical carrier and ± second-order sidebands can be obtained, while the higher sidebands which are even-order are omitted.

The output signals of the two MZMs have the same sidebands (i.e. optical carrier and two second-order sidebands), but each of the sideband has different phase due to the 45° phase difference introduced by the electrical phase shifter. In the output of the upper MZM shown in figure 2, all the three components have a phase of 0°. In the output of the bottom MZM, the -2nd-order sideband has a phase of $-90°$, the carrier has a phase of 0° and the 2nd-order sideband has a phase of 90°. Then, the two optical signals are sent into the directional coupler, which has a transmission matrix as expressed in eq. (1). In the output of the upper port, the phase of the upper MZM will not change while the phase of the bottom MZM will change 90°, as shown in figure 2. As a result, the two $+2$nd-order sidebands from the two MZMs are out of phase and cancelled each other. Only the carrier and -2nd-order sideband are reserved. Similarly, at the bottom port, the two -2nd-order sidebands are out of phase and cancelled each other. Only the carrier and $+2$nd-order sideband are obtained.

For the two ports of DPMZM, their optical fields can be written as

$$\begin{bmatrix} E_1(t) \\ E_2(t) \end{bmatrix} = \begin{bmatrix} \sqrt{1-c} & j\sqrt{c} \\ j\sqrt{c} & \sqrt{1-c} \end{bmatrix} \begin{bmatrix} E_{M1}(t) \\ E_{M2}(t) \end{bmatrix}$$

$$\propto E_{in}(t) J_0(m) \exp\left(j\frac{\pi}{4}\right) \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

$$+\sqrt{2}E_{\mathrm{in}}(t)J_2(m)\begin{bmatrix}\exp(-j2k\omega t)\\ \exp(j2k\omega t+j(\pi/2))\end{bmatrix}, \tag{1}$$

where $c = 1/2$ is the coupling coefficient of the directional coupler, $E_{\mathrm{M1}}(t)$ and $E_{\mathrm{M2}}(t)$ are the output signals of MZM1 and MZM2, respectively, $E_{\mathrm{in}}(t)$ is the incident light, m is the modulation index of MZM, ω refers to the frequency of the signals of the microwave, while $J_n()$ is the first nth-order Bessel function.

All signals from ports 1 and 2 are combined into one path with orthogonal polarisation directions through a PBC. The PBC selects the appropriate polarisation component of each signal at the input ports and combined the selected polarisation components at the output of the PBC. The two orthogonally-polarised optical signals are transmitted in the same fibre, as shown in figure 3.

With the optical carrier then controlled by an OF, the orthogonally polarised ± second-order optical sidebands are obtained. The application of PC1, which is a polarisation controller, aims to adjust the polarisation directions so that the two sidebands and the main axes of the PolM are aligned. The PolM equals to two parallel phase modulators (PMs) with complementary phase modulation indices connected by a polarisation beam splitter (PBS) and a polarisation beam combiner (PBC), as shown in figure 4.

As a complementary phase, the two optical sidebands are modulated through PolM by a driving signal $V_s s(t)$, where V_s is the amplitude and $s(t)$ is the normalised waveform. At the output of the PolM, the optical signal can be given by

$$\vec{E}_p(t) \propto E_{\mathrm{in}}(t)J_2(m)\Big\{\vec{x}\exp\left[-j2\omega t - j\beta s(t)\right] + \vec{y}\exp\left[j2\omega t + j\frac{\pi}{2} + j\beta s(t)\right]\Big\} \tag{2}$$

in which x- as well as y-directions represent two principal axes of PolM, $\beta = \pi V_s/V_\pi$ represents the phase modulation index of PolM, V_π means the half-wave voltage of PolM.

A time domain optical switch (OS) is placed after the PolM to select the modulated optical signal. The balanced photodetection is applied to suppress the distortion and background noise in the detected signal [20]. Adjust PC2 so that one of the principal axis of the polarisation beam splitter (PBS) will reach an angle of 45° to another principal axis of the PolM, then from the PBS the two output signals are generated.

$$\begin{aligned}E_{\mathrm{out1}} &\propto E_{\mathrm{in}}(t)\,J_2(m)\big\{\exp\left[-j2\omega t - j\beta s(t)\right] + \exp\left[j2\omega t + j\tfrac{\pi}{2} + j\beta s(t)\right]\big\}\\ E_{\mathrm{out2}} &\propto E_{\mathrm{in}}(t)\,J_2(m)\big\{\exp\left[-j2\omega t - j\beta s(t)\right] - \exp\left[j2\omega t + j\tfrac{\pi}{2} + j\beta s(t)\right]\big\}\end{aligned}, \quad T \le t \le T+\tau, \tag{3}$$

where T represents the starting moment and τ is the time duration of the generated pulse.

For a balanced detection, the balanced photodetector then receives the two output signals from the PBS. When $s(t)$ represents a parabolic waveform, the generated pulse after BPD can be expressed as

$$i(t) \propto E_{\mathrm{in}}^2(t)J_2^2(m) \times \cos\left[4\omega t + \frac{\pi}{2} + 2\frac{\beta}{\tau^2}(t-T)^2\right], T \le t \le T+\tau. \tag{4}$$

Thus, an mm-wave chirped pulse with a central frequency which is four times the LO frequency and a bandwidth of $2\beta/(\pi\tau)$ is generated.

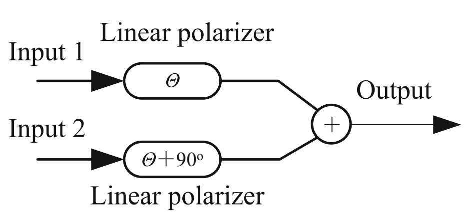

Figure 3. Polarisation beam combiner.

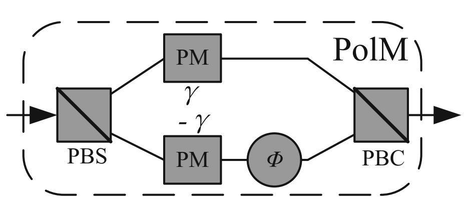

Figure 4. Polarisation modulator.

3. Simulation results and discussion

As presented in figure 1, a system which is a proof of concept is built on the basis of the OptiSystem platform to testify the scheme of the generation of chirped mm-wave pulse. The laser works at a wavelength of 193.1 THz and a power of 16 dBm. Each of the MZMs in the dual-output DPMZM has an insert loss of 5 dB and a modulation index of 1.88. The frequency of LO is 10 GHz. The central frequency of notch OF reaches 193.1 THz and the bandwidth stands at 10 GHz. The EDFA first amplifies the filtered optical signal with an increase of 20 dB and then the PBC makes the combination. The PolM has an insert loss of 5 dB and modulated by a parabolic pulse with a modulation index of 12.34

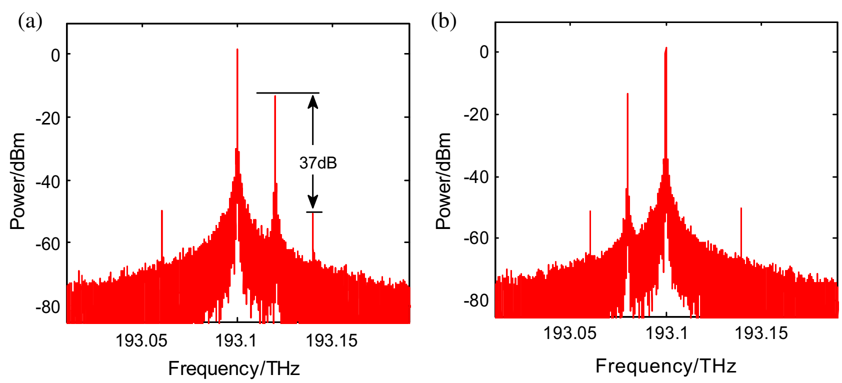

Figure 5. Optical spectra from (**a**) port 1 and (**b**) port 2 of the dual-output DPMZM.

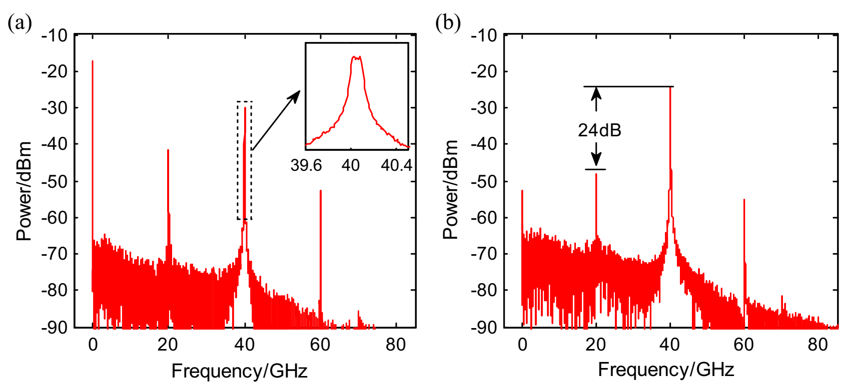

Figure 6. Electrical spectra for the signals generated by (**a**) single-end and (**b**) balanced detection.

and a time duration of 102 ns. The responsivity of BPD stands at 0.85 A/W.

The output optical spectra from the two ports of dual-output DPMZM are shown in figure 5. Both of them are single-sideband signals, one consisting of a carrier and a second-order sideband while the other consisting also of both a carrier and a second-order sideband, which agree well with the theoretical derivation of (1). The fourth-order sidebands, shown in figure 5, are also generated, with a power 37 dB lower than the second-order one.

In the case of the signals sent out by single-end and balanced detections, the electrical power spectra are shown in figure 6. By sending the optical signal from output1 of PBS into PD1 of the BPD detection from a single end can be obtained, which is shown in figure 6a. The linearly chirped signal with a carrier frequency of 40 GHz is generated, as shown in the inset of the figure. Direct current component (background noise) and distortion components with a frequency of 20 GHz and 60 GHz are also generated because of the fourth-order optical sidebands and the square-law detection. Figure 6b shows that through the balanced detection, both the noise and distortions are suppressed, and a signal-to-noise and distortion-ratio of 24 dB are obtained, as shown in figure 5.

Figure 7 shows a normalised waveform of the mm-wave linearly chirped pulse being generated. Figure 7a presents the waveform with a full-time duration and figure 7b shows the general view of the waveform over the time span of 1 ns to 1.5 ns. As shown in the figure, the cosine profiles have a time spacing of approximately 25 ps, corresponding to a frequency of approximately 40 GHz.

The instantaneous frequency of the generated pulse can be obtained by using the Hilbert transform and numerical differentiation. The instantaneous frequency of the sent-out pulse is shown in figure 8. The chirp rate has been maintained constant during the pulse duration, as expected for a linearly chirped pulse. As shown in the figure, the bandwidth of the waveform is 110 MHz, which agrees well with the calculated result of 109 MHz. The time-bandwidth product (TBWP) is calculated to be 11 considering the time duration of 102 ns. The TBWP is relatively small, but it can be efficiently increased by recirculating the phase modulation loop [21] or splitting the electrical parabolic signal [14].

The capability of pulse compression is also investigated. Figure 9 shows the autocorrelation function of the generated pulse. The PSR is about 7.4 dB. The full-width

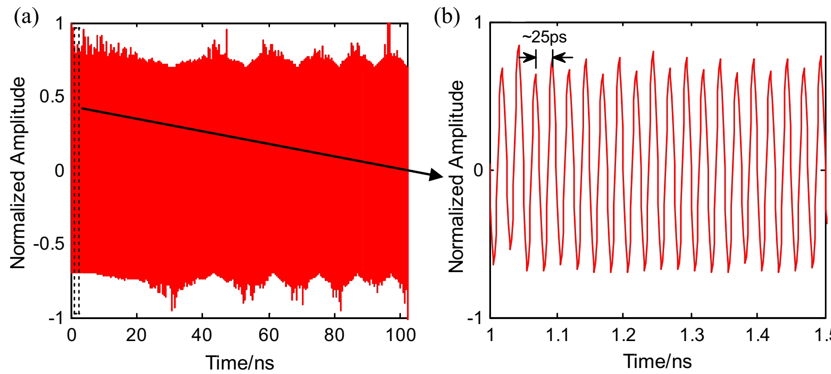

Figure 7. Generated pulse waveforms (**a**) with full time duration and (**b**) zoom-in with a time span of 1 to 1.5 ns.

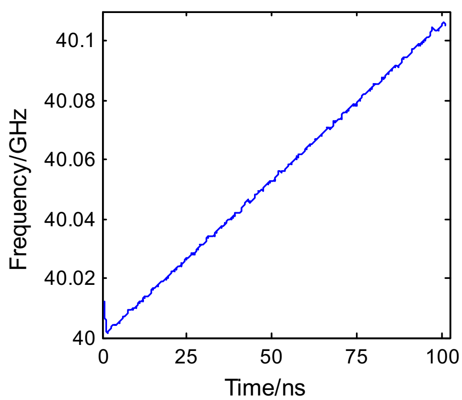

Figure 8. Instantaneous frequency of the generated pulse.

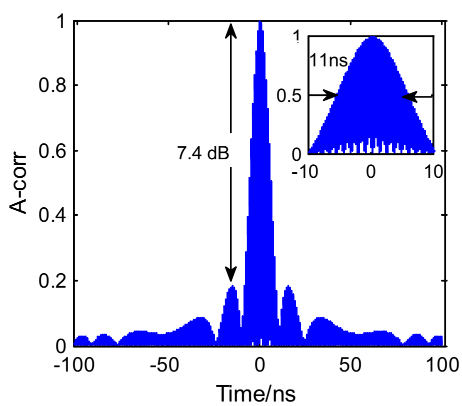

Figure 9. Autocorrelation function of the generated pulse.

at half-maximum (FWHM) of the compressed pulse is about 11 ns, corresponding to a pulse compression ratio (PCR) of 9.3. The PCR also can be improved by the approaches demonstrated in [14,21].

In the proposed approach, for the signal being sent out, its central frequency can be measured by adjusting how frequently LO occurs. Its minimum frequency is limited due to the notch bandwidth of OF (about 10 GHz). In comparison, its maximum frequency is limited by the notch bandwidth of BPD (more than 50 GHz). Thus, it can provide a large and continuous frequency tunable range, more than tens of GHz, which is much larger than the approach demonstrated in [19]. On the other hand, the FMF of the proposed approach is four, which can support high-frequency applications or ease the requirements of microwave drives compared to approaches reported in [12–18]. Furthermore, the generated pulse has good reconfigurability as the form of the generated pulse can be altered by changing the driving signal waveform applied to PolM.

4. Conclusions

In summary, a novel approach has been proposed and demonstrated to generate linear chirped signal that is mm-wave bearing great frequency tunable range. In the system, the focal point is the orthogonally polarised optical sideband generation, which is realised by using a dual-output DPMZM, a PBS and an OF. The $\pm$ second-order optical sidebands with orthogonal polarisation directions were generated and phase-modulated by a parabolic waveform in the PolM. The balanced detection was applied to suppress the noise and distortion in the generated signal. A linearly chirped pulse with a central frequency which is four times the LO frequency was achieved. The TBWP, PCR of the generated pulse were 11 and 9.3, respectively and the PSR was 7.4 dB. The proposal has both good reconfigurability and tunability, and, it may be non-stop frequency tuned with a wide range of about 10 GHz to over 50 GHz in principle.

Acknowledgements

Jun Liang is supported by the National Natural Science Foundation of China under Grant No. 61571461.

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