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Abstract. We demonstrated a photonic approach to generate a phase-continuous frequency-linear-chirped millimeter-wave (mm-wave) signal with high linearity based on continuous-wave phase modulated optical frequency comb and cascaded interleavers. Through linearly sweeping the frequency of the radio frequency (RF) driving signal, high-order frequency-linear-chirped optical comb lines are generated and then extracted by the cascaded interleavers. By beating the filtered high-order comb lines, center frequency and chirp range multiplied linear-chirp microwave signals are generated. Frequency doubled and quadrupled linear-chirp mm-wave signals of range 48.6 to 52.6 GHz and 97.2 to 105.2 GHz at chirp rates of 133.33 and 266.67 GHz/s are demonstrated with the ± 1 st and ± 2 nd optical comb lines, respectively, while the RF driving signal is of chirp range 24.3 to 26.3 GHz and chirp time 30 ms. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.52.12.126107](https://doi.org/10.1117/1.OE.52.12.126107)]

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1 Introduction

Linear frequency-chirped signal with continuous phase has attracted a lot of attention because of its vital applications in computer-aided numerical analysis,¹ frequency modulated continuous-wave applications,²⁻⁴ ultrafast wired and wireless communications,⁵ and imaging systems.^{6,7} The radar pulses, for example, are usually frequency chirped to improve the time-bandwidth product (compression ratio), thus to promote the range resolution under the same radar detection distance. Even though generation of such chirped millimeter-wave (mm-wave) signals can be achieved by electrical devices, it has faced great restriction in central frequency and chirp range, which play important roles in spatial and temporal resolutions. As a promising alternative, photonic generation of linear frequency-chirped signal can meet the requirements of high center frequency and broad chirp range. Photonic generation methods, such as direct frequency-to-time mapping technique^{8,9} and heterodyne-beating technique,^{10,11} have been proposed and achieved. However, the direct frequency-to-time mapping systems usually have a high complexity of pulse shaper system and a truly continuous chirp waveform is difficult to achieve because of the limited frequency resolution of the pulse shaper system. The heterodyne-beating system generated signal is influenced by the phase noise of the photonic source and the linearity is determined by the wavelength-sweeping laser, which poses a high performance request of lasers. Optical phase locked loop can significantly improve the phase noise performance of the heterodyne-beating technique, but this increases the complexity of the system.

In this paper, we proposed and experimentally demonstrated a photonic approach to generate a phase-continuous frequency-linear-chirped mm-wave signal based on

continuous-wave phase modulated optical frequency comb (OFC)¹² and cascaded interleavers. Through linearly sweeping the frequency of the radio frequency (RF) driving signal, high-order frequency-linear-chirped optical comb lines are generated. These high-order comb lines are then extracted by a common-path filter based on cascaded interleavers, avoiding the signal deterioration due to separated optical paths. By beating the filtered high-order comb lines, center frequency and chirp range multiplied linear-chirp microwave signals are obtained. Frequency doubled and quadrupled linear-chirp mm-wave of range 48.6 to 52.6 GHz and 97.2 to 105.2 GHz are demonstrated with the ± 1 st and ± 2 nd optical comb lines, respectively, while the RF driving signal is of chirp range 24.3 to 26.3 GHz and chirp time 30 ms.

2 Experimental Setup

The diagram of the frequency linearly chirped microwave signal generation system is shown in Fig. 1. It consists of a distributed feedback laser (DFB laser), broadband phase compensated comb-spacing continuous-swept OFC based on cascaded phase and intensity modulators (IMs),¹² an optical filter and cascaded optical interleavers. The 1553-nm optical carrier emitted from the DFB laser is phase and intensity modulated to generate high-order optical comb lines, where the frequency linearly chirped driving signal is provided by the microwave synthesizer (Anritsu model MG3694B, Morgan Hill, CA) with a range of 24.3 to 26.3 GHz and a chirp time of 30 ms, indicating a chirp rate of 66.67 GHz/s. The ± 2 nd comb lines are extracted through a 120-GHz passband optical filter and a 25 GHz/50 GHz interleaver (IL1) cascaded with a 50 GHz/100 GHz interleaver (IL2), which can be beat to generate frequency quadrupled linear-chirp mm-waves of frequency range 97.2 to 105.2 GHz by a broadband photodiode (PD). Also, the ± 1 st comb lines can be obtained at the other output

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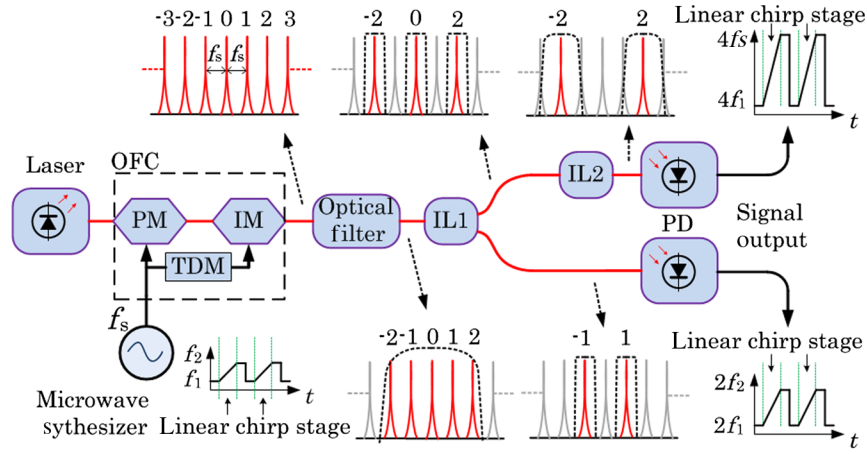


Fig. 1 Experimental setup for frequency linearly chirped microwave signal generation. PM, phase modulator; IM, intensity modulator; TDM, tunable electrical delay module; OFC, optical frequency comb; IL1, interleaver 1; IL2, interleaver 2; PD, photodiode.

port of the IL1, which are beat to generate frequency doubled linear-chirp mm-waves with the range of 48.6 to 52.6 GHz.

The optical carrier from the DFB laser can be represented as $E_c = E_0 \exp(j\omega_c t)$, where E_0 is the magnitude and $\omega_c = 2\pi f_c$ denotes the angular frequency. With the driving signal $V_s = \exp(j\omega_s t)$, where $\omega_s = 2\pi f_s$ denotes the angular frequency, the output of the cascaded phase modulator (PM) and intensity modulator (IM) can be expressed as:

$$E_{\text{comb}}(t) = \frac{E_c}{2} e^{j\omega_c t} \sum_{n=-\infty}^{+\infty} j^n \{J_n(\pi\beta_{\text{PM}}) + J_n[\pi(\beta_{\text{PM}} + \beta_{\text{IM}})] e^{j\pi\beta_{\text{DC}}}\} e^{jn\omega_s t}, \quad (1)$$

where β_{PM} denotes the PM electrical drive voltage normalized by its half-wave voltage, β_{DC} and β_{IM} are IM bias voltage and IM electrical drive voltage normalized by their half-wave voltages, n indicates the index of comb lines, and $J_n(x)$ stands for n 'th-order Bessel function of the first kind.

Then passing the optical comb lines of Eq. (1) through a 120-GHz passband optical filter and IL1, the ± 1 st comb lines can be extracted.

$$E_1(t) = -\frac{j}{2} E_c \{J_1(\pi\beta_{\text{PM}}) + J_1[\pi(\beta_{\text{PM}} + \beta_{\text{IM}})] e^{j\pi\beta_{\text{DC}}}\} \times [e^{j(\omega_c + \omega_s)t} - e^{j(\omega_c - \omega_s)t}]. \quad (2)$$

Also at the output of cascaded interleavers, the ± 2 nd comb lines can be obtained.

$$E_2(t) = -\frac{E_c}{2} \{J_2(\pi\beta_{\text{PM}}) + J_2[\pi(\beta_{\text{PM}} + \beta_{\text{IM}})] e^{j\pi\beta_{\text{DC}}}\} \times [e^{j(\omega_c + 2\omega_s)t} + e^{j(\omega_c - 2\omega_s)t}]. \quad (3)$$

Figures 2(a) and 2(b) exhibit the optical spectra of the ± 1 st and ± 2 nd comb lines spacing $2f_s$ and $4f_s$, respectively. It can be seen that the optical harmonics distortion suppression ratio in Fig. 2 exceeds 40 dB, therefore the effect of residual harmonics can be ignored.

The frequency-linear-chirped driving signal of the cascaded PM and IM can be represented as

$$V_s = \cos 2\pi \left(f_0 + \frac{1}{2} \gamma t \right) t, \quad (4)$$

where f_0 and γ denote the initial frequency and chirp rate, respectively. Applying the amplified driving signal in Eq. (4) to the system, the ± 1 st and ± 2 nd comb lines are generated. By beating the ± 1 st comb lines, the generated linear-chirp mm-wave signal is frequency doubled, while beating the ± 2 nd comb lines generates a frequency quadrupled linear-chirp mm-wave signal, as represented in Eqs. (5) and (6).

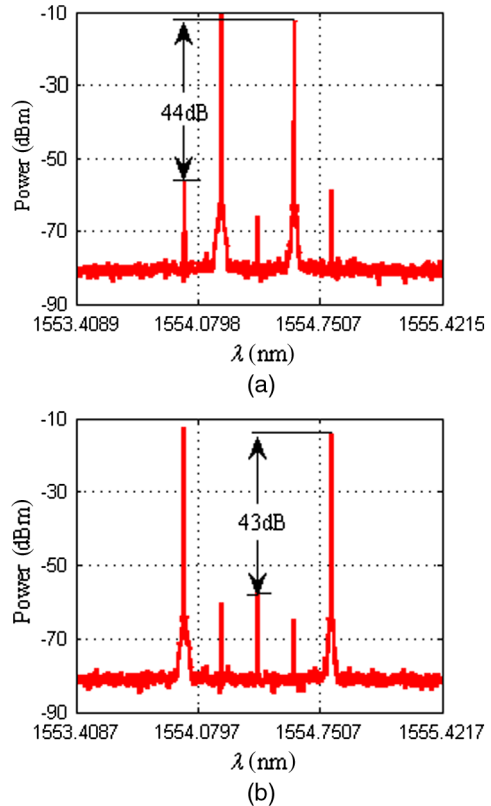


Fig. 2 Optical spectra of (a) the ± 1 st comb lines spacing $2f_s$ and (b) ± 2 nd comb lines spacing $4f_s$.

$$V_{m1}(t) = \cos 2\pi(2f_0 + \gamma t), \tag{5}$$

$$V_{m2}(t) = \cos 2\pi(4f_0 + 2\gamma t). \tag{6}$$

3 Experimental Results and Discussion

In order to verify the performance of the frequency linearly chirped mm-wave signal generation system, the 0th carrier and 1st comb line are extracted and beat by a 40-GHz bandwidth PD for the comparison with the original driving signal. The driving signal is frequency linearly chirped from 23.3 to 25.3 GHz with a chirp time of 30 ms, contributing to a chirp rate of 66.67 GHz/s. The spectrums of the RF driving signal and PD output signal are compared in Fig. 3. For the different powers of the RF driving signal and PD generated signal, we use the relative power to compare their performance. The spectrum of frequency chirp is shown in power relative to its single frequency peak power, and it has a relatively high power at the beginning and end, which might be attributed to the RF driving signal generator or the spectrum analyzer. As shown in Fig. 3, there exists no significant difference of performance between the original driving signal and the PD output signal.

Further generation of frequency linearly chirped mm-wave with the range of 48.6 to 52.6 GHz and 97.2 to 105.2 GHz in a chirp time of 30 ms can be achieved through extracting the ±1st and ±2nd comb lines, respectively.

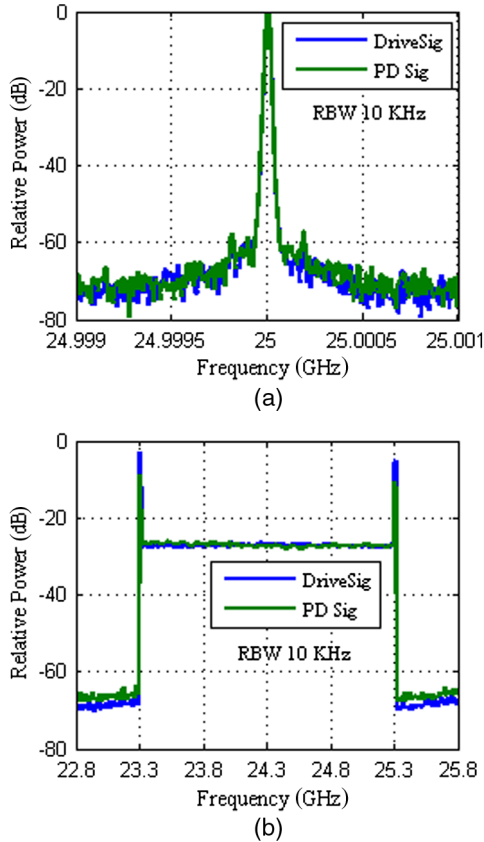


Fig. 3 Spectrum of (a) single frequency signal at 25 GHz and (b) frequency chirp with range of 23.3 to 25.3 GHz, driving signal (actual power of ~3 dBm) in blue line and PD output signal (actual power of ~-15 dBm) in green line with resolution bandwidth (RBW) of 10 KHz.

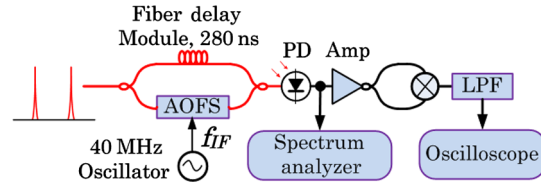


Fig. 4 Optical delayed self-heterodyne system. AOFS, acousto-optic frequency shifter; PD, photodiode; Amp, power amplifier; LPF, low-pass filter.

Due to the bandwidth limitations of PD and spectrum analyzer in our laboratory, the optical delayed self-heterodyne system^{13,14} is set up for further analysis as shown in Fig. 4.

Considering the linear-chirp stage as shown in Fig. 1 exclusively, the PD output and low-pass filtered mixer output can be represented as

$$V_{PD}(t) = \cos \left[2\pi(f_{IF} + n\gamma\tau)t + f_c\tau + nf_0\tau - \frac{n}{2}\tau^2 \right] + \cos \left[2\pi(f_{IF} - n\gamma\tau)t + f_c\tau - nf_0\tau + \frac{n}{2}\tau^2 \right], \tag{7}$$

$$V_{mix}(t) = \cos[2\pi(2n\gamma\tau)t + 2nf_0\tau - n\tau^2], \tag{8}$$

where f_{IF} denotes the frequency of the 40 MHz intermediate frequency (IF) signal applied to the acousto-optic frequency

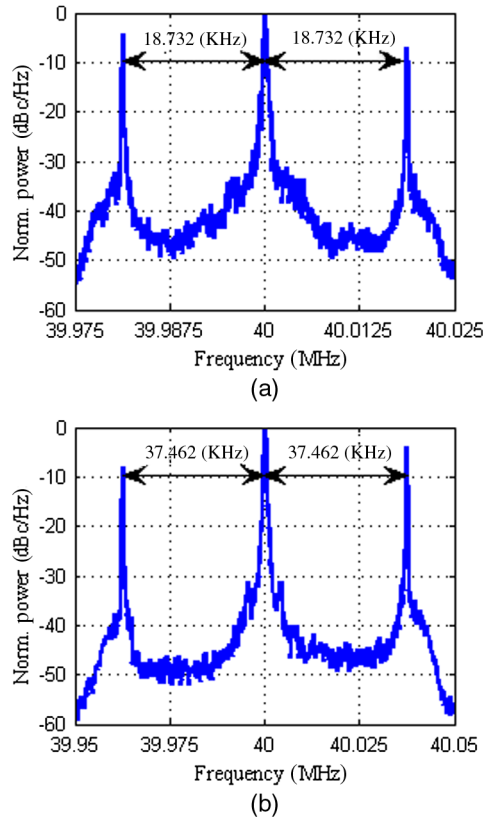


Fig. 5 Measured electrical spectrum of PD output signals with 1 Hz RBW. (a) The spectrum corresponds to the ±1 comb lines and (b) spectrum corresponds to the ±2nd comb lines.

shifter, and τ is the relative path delay introduced by the fiber delay module, which is about 280 ns.

The spectrum of the PD output is shown in Fig. 5 to exhibit the chirp characteristics of the frequency linearly-chirped mm-wave signals. Spectrums in Figs. 5(a) and 5(b) correspond to the delayed self-heterodyne signals of the ± 1 st comb lines and the ± 2 nd comb lines. The left and right peaks represent the spectrum of Eq. (7) while the peak at 40 MHz is due to the delay between the linear-chirp stages where $\gamma = 0$. Given the frequency shown in Fig. 5 and a relative path delay of about 280 ns, the chirp rate of comb lines can be calculated. According to the calculated chirp rate and chirp time of 30 ms, the chirp ranges of generated mm-waves are 4.014 and 8.028 GHz, respectively.

The high-speed oscilloscope captures the waveforms of Eq. (8) with a 10-ms time length, and the detailed figure is shown in Fig. 6(a). Through Hilbert transform of the waveforms, frequency tendency of the frequency doubled and quadrupled linear-chirp signals, $2\gamma t$ and $4\gamma t$, respectively, can be obtained, as shown in Fig. 6(b). They both exhibit high linear dependency, and the slopes of their linear fit curves are 133.69 and 267.37 GHz/s which are consistent with the chirp rates of 2γ and 4γ , respectively. Also Fig. 6(c) gives the frequency errors between the obtained frequency curve and its fit curve, which are about several hundreds of kilohertz, showing high linearity of the generated mm-waves.

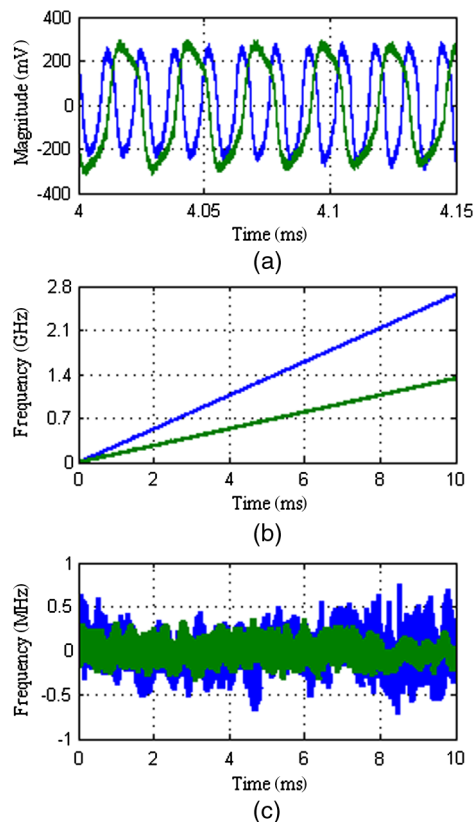


Fig. 6 (a) Captured waveforms of LPF output in time domain, (b) the extracted frequency curve, and (c) the frequency error between the obtained curve and the fitting curve, the green line and blue line correspond to the ± 1 st comb lines and ± 2 nd comb lines, respectively.

It is noticeable that our proposed system generates frequency-chirped mm-wave signals with high linearity as illustrated and exhibits no significant performance deterioration. However, the chirp rate of the frequency linearly chirped driving signal is limited by the microwave synthesizer, which then restricts that of the generated mm-wave signal. A frequency linearly chirped driving signal with a high chirp rate will further upgrade the performance of the system.

4 Conclusion

We have proposed and experimentally demonstrated a frequency linearly chirped mm-wave generation system with a wide chirp range and high linearity based on OFC and cascaded interleavers. MM-wave signals with frequency linearly chirped from 48.6 to 52.6 GHz and from 97.2 to 105.2 GHz in chirp time of 30 ms, which indicate chirp rates of 133.33 and 266.67 GHz/s, have been achieved. Owing to the common-path comb lines extraction based on cascaded interleavers which avoids the signal deterioration due to separated optical paths, the system exhibits no significant performance degeneration. It is flexible to change the chirp rate and range of the obtained mm-wave by controlling the driving signal. Future works will focus on increasing the chirp rate and chirp range, which can further promote applications in W-band communication, detection system, and instrumentation.

Acknowledgments

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