Broadband Frequency Swept Millimeter-Wave Source based on Cascaded Temporal Optical Pulse Shaping

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Abstract — **A new approach to generate high-quality broadband frequency swept millimeter-wave (mm-wave) waveforms based on photonics-assisted frequency up conversion of a low-frequency chirped drive signal has been proposed. This is made possible by using an unbalanced temporal pulse shaping system involving two cascaded Mach-Zehnder modulators both biased at the minimum transmission points. The proposed approach is verified by simulations. A frequency swept mm-wave pulse with its instantaneous frequency spanning from 40 to 100 GHz and a chirp rate of 66.7 GHz/ns is generated thanks to 40 times frequency up conversion. Two-fold improvement on the time-bandwidth product of the generated waveform is also achieved thanks to the cascaded modulation scheme.**

Keywords—Chirped pulse, Mach-Zehnder modulator (MZM), microwave photonics, millimeter-wave, suppressed carrier modulation, temporal pulse shaping (TPS)

I. INTRODUCTION

Broadband frequency swept millimeter wave (mm-wave) sources are of crucial importance in various applications such as modern radar systems, electronic countermeasures, high-speed wireless communications, and chirped pulse mm-wave computed tomography [1]. In the past few decades, microwave photonics [2] has become a promising solution to overcome the electronic bottleneck in mm-wave signal generation associated with the limited analog bandwidth of electronic circuits and sampling speed of digital to analog convertors. This is made possible owing to unique advantages of optics compared to its electronic counterparts, such as broader bandwidth, higher frequency, lower loss and better tunability.

Various photonics-assisted methods to generate frequency swept microwave and mm-wave pulses have been reported [3], including those based on optical spectral pulse shaping and wavelength to time mapping [4, 5], direct space to time pulse shaping [6], and photonic microwave filtering [7]. Time-bandwidth product (TBWP) is one of the most important figures of merit for the generated frequency swept mm-wave waveforms [8]. Most recently, TBWP expansion in photonic microwave waveform generation systems based on warped stretch transform has been demonstrated [9].

Photonic mm-wave pulse generation systems in [4-8] are based on direct shaping of optical or microwave seed pulses. One difficulty associated with these methods is the relatively poor quality of the generated waveforms with non-negligible deviations from the desired shape. This is originated from the imperfection of pulse shaping systems. An alternative approach to generate high quality mm-wave waveforms is based on frequency up-conversion of low frequency drive signals with the desired shape, which can be obtained by electronic means with high accuracy. Photonic generation of single-tone mm-wave waveforms based on microwave frequency up conversion has been achieved using an unbalanced temporal pulse shaping (UB-TPS) technique [10]. The microwave drive signal is firstly modulated on a pre-stretched optical pulse and frequency up-conversion is achieved by pulse compression due to unbalanced dispersion compensation. To generate frequency swept mm-wave waveforms from a single-tone microwave drive signal, a UB-TPS system incorporating high-order dispersion has been demonstrated [11]. However, the generated waveforms have limited frequency chirp with low TBWP values due to limited non-linear dispersions in the system.

In this paper, we report a novel scheme utilizing the UB-TPS technique to generate high-quality broadband frequency swept mm-wave waveforms with large frequency chirp and improved TBWP. In the proposed system, a precise low-frequency linearly chirped microwave signal is used as the seed drive signal. The chirp in the drive signal is translated into the generated mm-wave waveforms with precise linear frequency sweeping. Thanks to the direct frequency up-conversion in the UB-TPS system, not only the frequency bandwidth but also the chirp rate can be significantly increased. Moreover, our UB-TPS system is implemented in a cascaded modulation geometry. This new design, with proper DC-biasing and phase-matching conditions satisfied, further enhances the frequency multiplication factor, and more importantly, improves the TBWP of the generated mm-wave waveform by two-fold.

II. PRINCIPLE

Figure 1 (a) illustrates a conventional UB-TPS system consisting of a pulsed laser source and a Mach-Zehnder modulator (MZM) with two dispersion elements (DEs)

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connected to its input and output ports, respectively. The two DEs have opposite group velocity dispersion (GVD) values $\ddot{\Phi}_1\ddot{\Phi}_2 < 0$, but nonidentical in magnitude $|\ddot{\Phi}_1| \neq |\ddot{\Phi}_2|$. Here we ignore all the higher-order dispersion terms. An ultrafast optical pulse $g(t)$ is first pre-stretched by the first DE and then modulated by a linearly chirped microwave drive signal $V_{in}(t) = A\cos\left[(\omega_0 + at)t + \theta_1\right]$, where A, ω_0, a and θ_1 are the amplitude, central frequency, chirp rate and initial phase of the drive signal. The stretched and modulated optical pulse is finally compressed by the second DE. Here the UB-TPS system can be modeled as a typical balanced TPS system with two DEs having equal and opposite dispersions, followed by a residual DE with its dispersion given by $\Delta\ddot{\Phi} = |\ddot{\Phi}_2| - |\ddot{\Phi}_1|$.

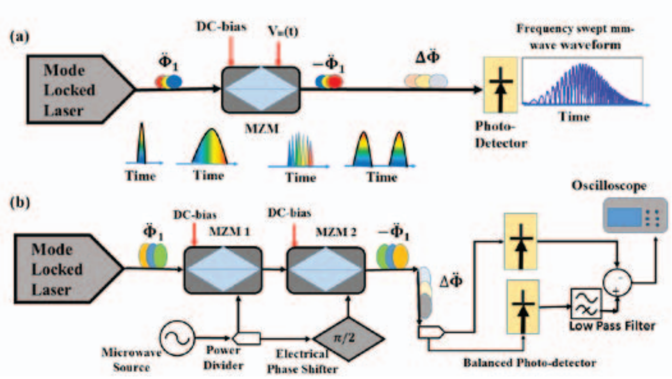


Fig. 1. Diagrams of (a) a conventional UB-TPS system and (b) the proposed UB-TPS system in a cascaded modulation scheme.

Mathematically, the electrical field at the output of the MZM can be expressed as:

$$e_{MZM}(t) = g'(t)\cos\left[\frac{\phi_1 + V_{in}(t)}{2}\right] \tag{1}$$

where $g'(t)$ is the stretched optical pulse by the first DE, and ϕ_1 is the corresponding constant phase change induced by the DC-bias voltage of the MZM. Choosing the constant phase modulation ϕ_1 as π would bias the MZM at the minimum transmission point (MITP) and suppress all even order sidebands along with the optical carrier. Under small signal condition, Eq. (1) can be simplified as

$$e_{MZM}(t) = g'(t)J_1(\beta_1)\left\{\begin{matrix}\sin\left[(\omega_c - \omega_m(t))t - \theta_1\right] \\ +\sin\left[(\omega_c + \omega_m(t))t - \theta_1\right]\end{matrix}\right\} \tag{2}$$

where $J_1(\bullet)$ is the first order Bessel function of the first kind, β_1 is the phase modulation index, ω_c is the nominal optical carrier frequency, and $\omega_m(t) = \omega_0 + at$ is the instantaneous modulation frequency of the microwave drive signal. Eq. (2) indicates double-sideband with suppressed carrier (DSB-SC) modulation.

At the output of the balanced TPS system, where the modulated optical pulse is fully compressed by a conjugate dispersion $-\ddot{\Phi}_1$, the output signal $s(t)$ can be expressed as the convolution between the input ultrashort optical pulse and the Fourier transform of the intensity modulation function [10]. We assume the ultrashort optical pulse is a temporal impulse function. Then the convolution can be simplified as

$$s(t) = E(\omega - \Delta t) + E(\omega + \Delta t)\Big|_{\omega = t/\ddot{\Phi}_1} \tag{3}$$

where $E(\omega)$ is the Fourier domain representation of the chirped microwave drive signal, and $\Delta t = \omega_0\ddot{\Phi}_1$ is a time delay as the result of the balanced TPS. Two twin pulses are obtained corresponding to the two first-order modulation sidebands.

The twin pulses are further stretched by the residual dispersion and a high-frequency mm-wave waveform can be obtained by beating the stretched and delayed pulses at a high-speed photodetector (PD). This can also be understood by the fact that the residual dispersion mirrors the optical pulse spectrum, which is modulated by the chirped microwave drive signal, to a scaled temporal waveform owing to the dispersion-induced wavelength-to-time mapping [12]. This mapping relation is assured if $\Delta\ddot{\Phi} > (2\Delta t)^2/\pi$, also known as the temporal far field Fraunhofer condition.

Therefore, at the output of the whole UB-TPS system, a frequency swept waveform with its instantaneous frequency being up-converted from the original microwave drive signal is generated, which can be expressed as

$$V_{out}(t) \propto g''(t)\cos\left[\left(M\omega_0 + M^2 at\right)t\right] \tag{4}$$

where $g''(t) = g(t) * \exp\left(j\frac{\pi}{2\Delta\ddot{\Phi}}t^2\right)$ is the envelope of the generated waveform, (*) denotes the convolution operation. The frequency multiplication ratio, *M*, is determined by the dispersion imbalance as $M = 2|\ddot{\Phi}_1|/\Delta\ddot{\Phi}$ [10].

Note that as the low frequency microwave drive signal can be synthesized by electronic means with a high precision, a high-quality mm-wave waveform with the desired shape can be obtained after direct frequency up-conversion in the UB-TPS system. Compared to the original microwave drive signal, the frequency bandwidth has been increased *M* times and the chirp rate M^2 times.

Moreover, in this paper we also propose a UB-TPS system implemented in a cascaded modulation geometry. As shown in Fig. 1(b), two cascaded MZMs both biased at MITPs are used to modulate the pre-stretched optical pulse. The same microwave signal $V_{in}(t)$ is divided to drive both MZMs. A broadband electrical phase shifter is used to provide an initial phase difference $\Delta\theta$ between two frequency chirped drive signals. The modulation signal applied to the second MZM then becomes $V_{in2}(t) = A\cos\left[(\omega_0 + at)t + \theta_2\right]$, where $\theta_2 = \theta_1 - \Delta\theta$ is the initial phase. With both MZMs biased at MITPs, the electrical field at the output of the second MZM is expressed as [13]:

$$e_{MZM2}(t) = g'(t)J_1(\beta_1)J_1(\beta_2)\times \left\{ \begin{array}{l} \cos\left[(\omega_c - 2\omega_m(t))t - \theta_1 - \theta_2\right] + \cos(\omega_c t - \theta_1 + \theta_2) \\ + \cos(\omega_c t + \theta_1 - \theta_2) + \cos\left[(\omega_c + 2\omega_m(t))t + \theta_1 + \theta_2\right] \end{array} \right\} \quad (5)$$

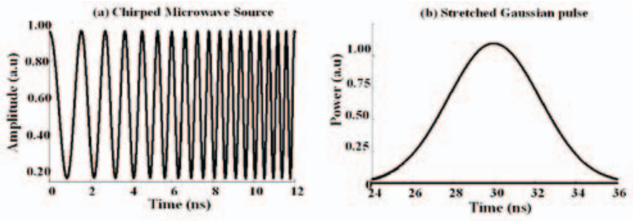
where β_2 is the phase modulation index of the second MZM.

According to Eq. (5), if a phase matching condition $\Delta\theta = \theta_1 - \theta_2 = 1/2\pi$ is satisfied, the optical carrier is totally suppressed and only two second-order modulation sidebands are obtained. Therefore, based on the similar concept in the single-MZM-based system, the proposed UB-TPS system in a cascaded modulation scheme offers improved frequency multiplication capability of $M = 4|\ddot{\Phi}_1|/\Delta\ddot{\Phi}$. In addition, this new design also enables two-fold improvement on the TBWP of the generated frequency-swept mm-wave pulses.

III. SIMULATION RESULTS

The proposed approach for broadband frequency-swept mm-wave source based on direct frequency up-conversion of a low frequency chirped microwave source using a cascaded UB-TPS system is verified by numerical simulations performed using a commercial software (VPItransmissionMaker), assuming main experimental system parameters as in [10].

A passive mode-locked laser generates ultrashort optical pulses with a Gaussian shape and a full-width half maximum (FWHM) pulse width of 500 fs. The optical pulses are pre-stretched by the first DE with a GVD value of $\ddot{\Phi}_1 = 955.4\ ps^2/rad$. The stretched pulse serves as the optical carrier and is modulated by the microwave drive signal at two cascaded MZMs that are both biased at MITPs. Here a positively chirped microwave signal drives both MZMs. The instantaneous frequency sweeps from 1 to 2.5 GHz in a span of 12 ns. To fulfill the phase matching condition in cascaded modulation, a broadband (1-2.5 GHz) frequency-independent 90° microwave phase shifter is inserted between two MZMs.


(a) Chirped Microwave Source

(b) Stretched Gaussian pulse

(c) Output at MZM 1

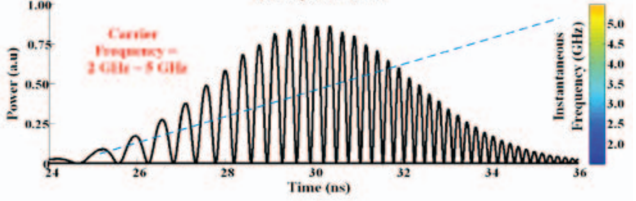
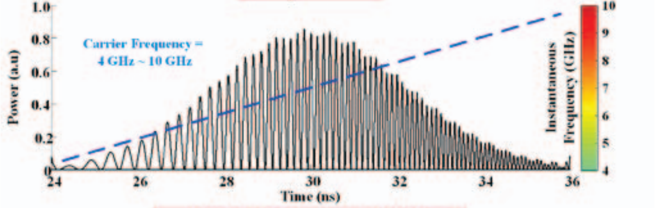


Fig. 2. (a) The chirped microwave drive signal; (b) The stretched optical pulse as a carrier; (c) Output at the first MZM.

Figure 2(a) shows the chirped microwave signal driving both MZMs and Fig. 2(b) depicts the pre-stretched optical pulse serving as an optical carrier over which the microwave drive signal is imposed on. The modulated optical pulse at the output of the first MZM is shown in Fig. 2(c). Instantaneous modulation frequency, which is estimated by Hilbert transform, ranges from 2 to 5GHz. Frequency doubling due to the DSB-SC modulation is clearly demonstrated.

The output of the second MZM is shown in Fig. 3(a). It is clearly verified that cascaded modulation with proper DC biasing and phase matching conditions offers further two-fold improvement in frequency multiplication and TBWP.

(a) Output at MZM 2



(b) Generated chirped mm-wave pulse

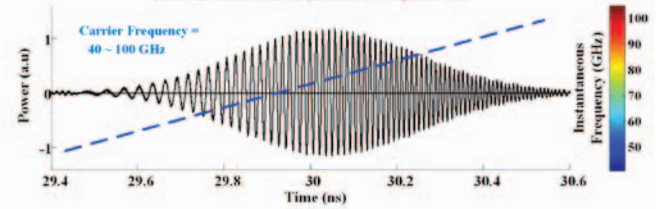


Fig. 3. (a) Output at the second MZM; (b) the generated frequency swept mm-wave pulse at the output of the whole system.

The modulated pulse is then sent to the second DE with a GVD of $\ddot{\Phi}_2 = -859.86\ ps^2/rad$. This is corresponding to an equivalent residual dispersion of $\Delta\ddot{\Phi} = -95.54\ ps^2/rad$. The generated frequency swept mm-wave pulse at the output of the whole UB-TPS system is shown in Fig. 3(b). Here balanced photodetection is employed not only to obtain DC-free waveform, cancel laser noise and common mode noise but also to improve the signal-to-noise ratio of the generated waveform. The instantaneous oscillation frequency is linearly spanning from 40 to 100 GHz with a chirp rate of 66.7 GHz/ns. A total 40× frequency multiplication has been achieved, which agrees well with the theoretical prediction of $M = 4|\ddot{\Phi}_1|/\Delta\ddot{\Phi}$. Note that 2× multiplication comes from MITP biasing, another 2× is contributed by the cascaded modulation, and 10× is due to pulse compression in the UB-TPS system. The 3 dB TBWP of the generated mm-wave waveform is estimated to be 15.7. Compared to the original microwave drive signal, an overall four-fold improvement on TBWP has been achieved on the generated frequency swept mm-wave waveform.

IV. DISCUSSIONS

One challenge in implementing the proposed technique is that a broadband frequency-independent 90° microwave phase shifter is required so as to maintain the phase matching relationship as outlined in Section II. Conventional electronic phase shifters fall short in wideband operation. Fortunately, RF photonic phase shifters have shown superior performance, such as wider bandwidth and larger tunable range [14] and can be employed in the proposed system to provide the required wideband phase shift.

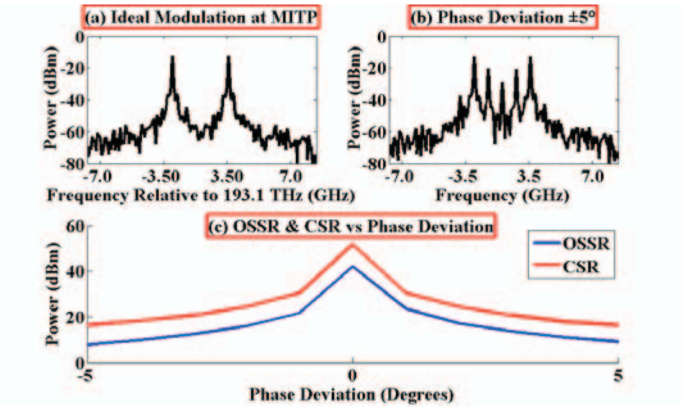


Fig. 4. Frequency spectra of modulated continuous wave optical carrier at 1.75 GHz by cascaded MZMs biased at MITP with (a) ideal 90º phase shift and (b) phase deviation of ±5°. (c) OSSR and CSR under different phase deviations.

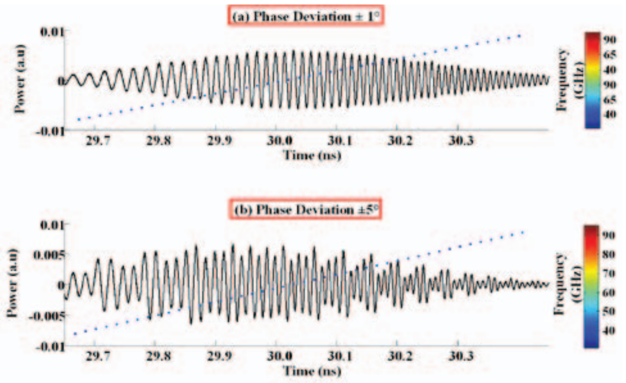


Fig. 5. (a) Output at a balanced PD for tolerable distortion (b) High distortion due to large phase offset.

An RF photonic phase shifter may produce phase deviation from the desired value of 90°. The impact of non-ideal phase shift is investigated. A cascaded UB-TPS system with a continuous wave (CW) optical carrier centered at 193.1 THz is first studied. A single-tone microwave drive signal at 1.75 GHz is used to drive both MZMs. Power distributions among carrier and different sidebands indicate the performance of frequency multiplication. Fourier domain representations of the modulated signal under different phase deviations are shown in Fig. 4. As we can see from Fig. 4(a), an ideal 90° microwave phase shift completely suppresses the optical carrier and unwantted sidebands, leading to good frequency quadrupling. However, a phase deviation of 5° results in the optical carrier gaining strength along with the first-order sidebands, as shown in Fig. 4(b). This will cause a distortion in the frequency quadrupled signal as the harmonics interfere with the spectral purity of the modulated waveform.

Optical sideband suppression ratio (OSSR), defined as the ratio of the power between the desired and undesired sidebands, and carrier suppression ratio (CSR), denoting the strength of the desired sideband with respect to the carrier, are used to characterize the impact of non-ideal phase matching, as shown in Fig. 4(c). To allow both OSSR and CSR larger than 20 dB, a tolerable phase deviation is estimated to be ±1°.

The impact of non-ideal phase shift on the generation of frequency swept mm-wave waveform is also investigated. Figure 5 shows the obtained mm-wave pulses with non-ideal phase shifts. It can be seen that a phase deviation of ±5° will significantly distort the shape of the generated waveform while the linear frequency chirp can be maintained.

V. CONCLUSION

We have proposed and demonstrated a novel photonic microwave frequency up conversion scheme for generation of high-quality broadband frequency swept mm-wave pulses. This is made possible based on unbalanced temporal optical pulse shaping in a cascaded modulation scheme. A chirped mm-wave pulse with its instantaneous frequency sweeping from 40 to 100 GHz and a chirp rate of 66.7 GHz/ns has been generated owing to 40 times frequency up conversion of a low frequency chirped microwave drive signal. Both frequency multiplication ratio and TBWP of the generated mm-wave waveform have been improved by 2 times compared to the conventional UB-TPS method where a single MZM is used.

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