Photonic Generation of Radar Signals with 30 GHz Bandwidth and Ultra-High Time-Frequency Linearity

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Photonic generation of radio-frequency signals has shown significant advantages over the electronic counterparts, allowing the high precision generation of radio-frequency carriers up to the terahertz-wave region with flexible bandwidth for radar applications. Great progress has been made in photonics-based radio-frequency waveform generation. However, the approaches that rely on sophisticated benchtop digital microwave components, such as synthesizers and digital-to-analog converters have limited achievable bandwidth and thus resolution for radar detections. Methods based on voltage-controlled analog oscillators exhibit high time-frequency non-linearity, causing degraded sensing precision. Here, we demonstrate, for the first time, a photonic stepped-frequency (SF) waveform generation scheme enabled by MHz electronics with a tunable bandwidth exceeding 30 GHz and intrinsic time-frequency linearity. The ultra-wideband radio-frequency signal generation is enabled by using a polarization-stabilized optical cavity to suppress intra-cavity polarization-dependent instability; meanwhile, the signal’s high-linearity is achieved via consecutive MHz acousto-optic frequency-shifting modulation without the necessity of using electro-optic modulators that have bias-drifting issues. We systematically evaluate the system’s signal quality and imaging performance in comparison with conventional photonic radar schemes that use high-speed digital electronics, confirming its feasibility and excellent performance for high-resolution radar applications.

Introduction.—Radar sensing has been progressing into the millimeter-wave (MMW, 30-300 GHz) and terahertz-wave (THz-wave, 0.1-10 THz) regions to operate with ultrawide bandwidth for growing demands of high spatial resolution imaging in real-world applications, such as non-destructive testing, automotive driving assistance, industrial quality inspection, and non-invasive medical imaging [1–3]. However, the development of wideband radar has posed significant challenges to conventional electronic technologies, especially in the synthesis of ultra-broadband signals. In particular, the bandwidth of direct digital synthesizers and digital-to-analog converters (two commonly used and essential components for signal generation) are constrained to a few gigahertz by the limited clock speed [4]. Moreover, these devices have shown significant degradation in both efficiency and noise level when approaching higher frequencies via multi-stage frequency up-conversion [5]. Additionally, multi-stage frequency multiplexing and spectrum stitching for bandwidth broadening introduce noise and spectrum spur induced by device nonlinearity and interference [6], which compromises overall sensing accuracy and performance.

Photonics-assisted radar shows the potentials to overcome the drawbacks in the electronic counterparts mentioned above, especially in bandwidth broadening [7], low-noise up-conversion [8], and simple down-conversion and demodulation [9]. However, existing photonic approaches for radar signal generation still rely on bulky, high-speed benchtop electronics, or lossy and elaborately biased electro-optic modulators (EOMs), limiting the achievable bandwidth, long-term operating stability, and ultimately the practicality [7, 10]. Alternative approaches using dispersion-based time-stretch [11] and frequency-sweeping light sources [12, 13] have also shown promising bandwidth capacity. However, these techniques remain challenging to meet simultaneously the high frequency-time linearity for accurate ranging without using pre-distorted control signals for linearity compensation and the wide bandwidth for a fine spatial resolution to cope with the real-world, resolution-demanding applications.

In this paper, we demonstrate, for the first time, an MHz electronics-enabled photonic synthesizing of stepped-frequency (SF) signal with tunable bandwidth exceeding 30 GHz and an inherent high frequency-time linearity. Because of using a polarization-maintaining optical cavity against the ambient environment perturbation and the stable acousto-optic frequency-shifting modulation without the bias-drifting issues from EOMs, the demonstrated system reaches a signal-to-noise ratio (SNR) of above 34 dB in signal generation comparable to those generated by high-end benchtop electronics. Simultaneously, the constant frequency shift and cavity round-trip time ensure an inherent high frequency-time linearity with a maximum deviation below 2.5 MHz throughout the bandwidth for accurate detection. We experimentally compare a radar system using the demonstrated scheme with a conventional photonic radar that relies on a high-speed waveform generator, clearly showing its comparable performance in radar imaging. With the achieved bandwidth exceeding 30 GHz, this demonstrated approach provides a viable basis for ultra-wideband microwave waveform synthesis for future ultra-
waveforms for radar sensing owing to their benefits of comparison to linear frequency modulated (LFM) signals. The received signal is demodulated for ranging and imaging [16]. Finally, a coherent optical receiver will demodulate the optical SF signal with conversion realized by mixing the optical SF signal with an optical comb filter. A simple optical-RF up-conversion is defined as

\[ \omega_{SF} = 2 \pi k \Delta \tau \]

where \( \Delta \tau \) is the incremental frequency, and \( k \) is the chirp rate [18], as depicted in Fig. 1(b). Advantageously, SF radars require a much lower digitizing speed (down to only one sample per step-time) than the LFM radar receivers bounded by the Nyquist sampling theorem. This characteristic allows the photonic SF radars to generate much less data while sustaining the same resolution, enabling low-consumption edge computing for resolution-demanding applications such as hand gesture recognition and object identification [19]. Moreover, the SF waveforms have shown other advantages over the LFM signals. For instance, it possesses an increased dynamic range due to each frequency step's narrow instantaneous frequency side is mainly contributed by the roll-off of the RF-domain as well as the noise floor (input disconnected) of the measuring apparatus (Agilent E4448A). It confirms the 25 GHz SF bandwidth, tantamount to a theoretical range resolution of 6 mm. The temporal waves and the corresponding frequency-time relations are presented in Fig. 2(c) and (d), respectively. These plots demonstrate that each frequency step only contains a single oscillating frequency and is progressively shifted after a specific dwell time (i.e., the round-trip time of the FSL). The time-domain envelope roll-off at the higher frequency side is mainly contributed by the roll-off of the OBPF, which is confirmed by the spectral measurements in both the optical (Fig. 2(a)) and RF domain (Fig. 2(b)). A further linearity analysis is carried out by comparing the difference between the experimental results (extracting the frequency of the time-domain signal in each frequency step) and the corresponding values of the first-order polynomial fitting, which is shown as the deviation in Fig. 2(e). The linearity analysis reveals a ladder-like frequency-time feature with a maximum deviation below 2.5 MHz throughout the 25 GHz bandwidth. The deviation is overestimated and is limited by the resolution of the digital processing within a finite time window. This feature ensures the high linearity of the SF format, which is hard to achieve using laser sweeping or voltage-controlled oscillators without an active feedback control loop or pre-distorted RF signals generated from high-resolution MMW and THz-wave radar systems.

**Experiments and Results.**—The demonstrated SF waveforms are generated through recirculating an optical rectangular pulsed signal originated from chopping a continuous wave (CW) laser in a frequency-shifting loop (FSL) [14], diagrammed in Fig. 1(a). An acousto-optic modulator (AOM) precisely shifts the pulse frequency for each round-trip, offering inherent ultra-high frequency-time linearity and ultra-fast frequency shifting. Moreover, the AOM shifted signal avoids the generation of spectrum harmonic spurs, which is an outstanding advantage over the approach using EOMs for single-sideband modulation (SSB) that suffers from bias-drifting and parasitic harmonics [10, 15]. An optical bandpass filter (OBPF) is used to determine and tune the bandwidth of the optical and thus the RF SF signals to satisfy diverse resolution requirements (range resolution is defined as \( c/2B \), where \( B \) is the synthesized bandwidth of the signal). Meanwhile, an erbium-doped fiber amplifier (EDFA) compensates for the optical modulation and propagation energy losses. It is worth mentioning that the pulse dwelling time set by an optical switch (OS) should be less than the round-trip time of the FSL to avoid inter-pulse cross-talk. A simple optical-RF up-conversion is realized by mixing the optical SF signal with a frequency-shifted CW laser signal in a photodetector (PD). Finally, a coherent optical receiver will demodulate the received signal for ranging and imaging [16].

Fig. 1(b) shows the principle of the SF signal, in comparison to linear frequency modulated (LFM) signals, which are both widely used as pulse-compression waveforms for radar sensing owing to their benefits of higher mean powers while sustaining superior resolution [17]. The operation principles of the SF signal and the LFM signal have fundamental but subtle differences; intuitively, the SF signal is a discretely sampled version of the LFM signal, as shown in Fig. 1(b). In radar applications, the SF radar encodes the time delay (\( \Delta \tau \)) of the reflected signal as phase differences with respect to the reference signals (\( \omega_{SF} = 2 \pi n \Delta f \Delta \tau \), where \( \Delta f \) is the incremental frequency, and \( n = 1, ..., N, N \) is the total number of frequency steps). The LFM radar forms a new oscillating frequency proportional to the round-trip time \( \Delta \tau \) (\( \omega_{LFM} \propto 2 \pi k \Delta \tau \), where \( k \) is the chirp rate [18]), as depicted in Fig. 1(b). Advantageously, SF radars require a much lower digitizing speed (down to only one sample per step-time) than the LFM radar receivers bounded by the Nyquist sampling theorem. This characteristic allows the photonic SF radars to generate much less data while sustaining the same resolution, enabling low-consumption edge computing for resolution-demanding applications such as hand gesture recognition and object identification [19]. Moreover, the SF waveforms have shown other advantages over the LFM signals. For instance, it possesses an increased dynamic range due to each frequency step's narrow instantaneous frequency-time feature with a maximum deviation below 2.5 MHz throughout the 25 GHz bandwidth. The deviation is overestimated and is limited by the resolution of the digital processing within a finite time window. This feature ensures the high linearity of the SF format, which is hard to achieve using laser sweeping or voltage-controlled oscillators without an active feedback control loop or pre-distorted RF signals generated from high-resolution MMW and THz-wave radar systems.
Bandwidth and frequency shift tunability (changing $\Delta f$) are prominent metrics when deploying SF signals for various applications as two key sensing parameters are decided accordingly, i.e., the range resolution, $c/2B$ and ambiguity, $c/(2 \times \Delta f)$. In principle, the demonstrated system can achieve arbitrary bandwidth tuning by changing the passband and central frequency of the OBPF, thereby enabling range resolutions down to mm level. However, in practice, such broadband synthesizing is challenging for single-mode fibers (SMFs), especially when polarization will be further scrambled in the optical cavity, deteriorating the phase stability, signal coherence, and ultimately the sensing performance. As shown in Fig. 3(a), the time-frequency plot of the SF signal generated through an un-optimized FSL using SMF is challenging to achieve a bandwidth of 12 GHz. Fig. 3(b) provides an insight into the time-frequency plot, revealing the amplitude fluctuations across different frequency steps, caused by the polarization and gain instability.

To provide more insights into the signal quality, we compare the SNR of the signal generated using different schemes. Fourier analysis using 25 ns, time-domain...
signal clips between SMF-based system and PMF-based system are shown in Fig. 3(e) and Fig. 3(f), respectively. The results are sampled at two instances, i.e., 10-time (blue) and 60-time (red) recirculation, revealing a more than 14 dB SNR improvement with an SNR of 34. In the meantime, the result of 200-time recirculation in the optimized system exhibited in Fig. 3(f) (yellow) also proves that the SNR does not obviously degrade as the pulse recirculation time increases, indicating a low stability penalty from the FSL noise accumulations. Moreover, we compared the SF signal generated between the PM-based FSL and an arbitrary waveform generator (AWG, Keysight M8195A 65GSa/s). Signal quality analysis in Fig. 3(g) shows that the demonstrated system sustains an SNR above 34 dB after 60-time recirculation in the PMF-based FSL compared with 39 dB SNR from the high-end electronics. The results also proved that the demonstrated system could replace high-speed, noisy electronic synthesizers to generate ultra-broadband signals directly at the carrier band for accurate MMW and THz-wave sensing.

In order to demonstrate the competitive performance and feasibility, we compare radar imaging performance based on the SF signal generators with those using high-speed electronic AWGs as shown in Fig. 4. 2D imaging results are conducted based on the inverse synthetic aperture radar (ISAR) technique. Comparison experiments that use ultra-fast electronics (Keysight M8195A, 65GSa/s, ~25 GHz analog bandwidth) for generating both SF and LFM signals are carried out based on the schematic shown in Fig. 4(a) while keeping the same bandwidth (5.76 GHz), step numbers (72 steps), repetition rate (25 us), and RF radiation power (~ 10 dBm), as illustrated in Fig. 4(c). It should be noted that the signal bandwidth in the demonstrations were chosen due to the bandwidth availability of the RF antenna, without losing comparison generality. Wideband-RF signals generated by the AWG modulate a CW laser carrier through a single-sideband modulation before beating with a separate optical carrier for optical-RF up-conversion. As shown in Fig. 4(b), three-cylinder objects mounted on a rotating platform are used as the target. ISAR imaging results in Fig. 4(d) are chosen at two particular instances for an adequate performance illustration and comparison, proving that the demonstrated system is reliable for imaging moving objects. Notably, the demonstrated system successfully reconstructed ISAR images of the objects without distinguishable differences from those based on the AWG. It should be noted that a minor frequency step (Δf) can be achieved by cascading two AOMs with the opposite frequency shift (e.g., a frequency shift from -10 to +10 MHz has been demonstrated in [20]) to achieve an unambiguous range over 100 meters, which is comparable to the 120 meters unambiguous range window (1.25 MHz frequency shift) from the CARABAS system - a very early airborne synthetic aperture radar that employed SF signals - mounted on an aircraft [21].

Conclusions.---In conclusion, we demonstrated a photonic SF waveform generation with a tunable bandwidth of >30 GHz and intrinsic high-linearity for high-resolution and accurate radar detections. By stabilizing polarization in the optical FSL loop, we significantly improve the SNR of the SF signals from 17 dB to 34 dB with a low noise accumulation penalty, allowing imaging performance comparable to those using high-speed apparatus. The demonstrated system enables high-resolution radar sensing and represents an attractive combination of wideband signal synthesizing, high SNR, and reduced hardware requirements. This work serves as a pilot study and experimental basis for further chip-based radar integration using on-chip devices [22], opening the door to future ultra-high-resolution, miniaturized, and mobile millimeter-wave devices with prime performance and flexibility.

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