11-GHz-Bandwidth Photonic Radar using MHz Electronics

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The ever-increasing demand for high resolution and real-time recognition in radar applications has fuelled the development of electronic radars with increased bandwidth, high operation frequency, and fast processing capability. However, the generation and processing of wideband radar signals increase the hardware burden on complex and high-speed electronics, limiting its capability for applications that demand high spatial resolutions. Progress is being made, photonics-assisted radars offer higher frequencies but still heavily rely on costly and sophisticated high-frequency electronic devices such as benchtop digital microwave waveform generators that fundamentally constrain the bandwidth and the practical utility. Here, for the first time, a photonics-based radar with >11 GHz bandwidth (exceeding 20 GHz without RF antenna bandwidth limitation) driven and processed by simple MHz-level-electronics-based acoustic-optic modulation is demonstrated, which radically eliminates the requirement for ultra-fast GHz-speed electronics for wideband radar signal generation and processing. This wideband radar achieves centimeter-level spatial resolution and a real-time imaging rate of 200 frames s\(^{-1}\), allowing for high-resolution detection of rapidly moving blades of an unmanned aerial vehicle. This radar provides an important technological basis for next-generation broadband radars with greatly reduced system complexity essential to ubiquitous sensing applications such as autonomous driving, environmental surveillance, and vital sign detection.

1. Introduction

Radio detection and ranging (radar), as an essential function, plays an important role in civilian and security applications such as autopilot assistance, anti-collision warning, target identification, hand gesture movement recognition, and remote heartbeat detection.[1–5] Radar ranging and imaging is based on the principle of emitting time, or frequency modulated microwave signals to illuminate objects of interest; the consecutive snapshots of objects’ spatial and velocity information are encoded on the returned analog signals in the form of time delay and instantaneous phase variation, which are retrieved by digital signal processing. Modern applications demand radars to precisely locate and recognize objects, requiring fine spatial resolution that inversely depends on the radar signal bandwidth.[2] However, the realization of ultra-broadband electronic radars accommodated by high carrier frequencies is fundamentally constrained by achievable electronic circuit clock rates of typically a few gigahertz (GHz), as well as the increased complexity in frequency up/downconversion.[6]

Furthermore, for sampling echo signals at receivers, the use of wideband radar signals not only increases the hardware burden in particular for analog-to-digital converters (ADCs), but also reduces the sampling precision.[7] Recently, the emergence of photonics-assisted radar technology has provided a promising approach to break the electronic bottleneck of bandwidth and operation frequency, on the basis of the transparent and ultra-wide fractional bandwidth at optical frequencies (typically at hundreds of terahertz) for microwave radar signal generation and processing.[6,8–10] Using microwave photonic technology,[11,12] greatly enhanced radar ranging performance has been demonstrated; for example, ultra-broadband radar that goes beyond GHz-level bandwidth enables an unprecedented spatial resolution at centimeter-level,[13,14] thus allowing for identifying fine features of objects for accurate recognition. Photonics-assisted multiple-input and multiple-output radars[15] and multi-band radars[16–18] have been demonstrated with enhanced flexibility, underpinned by low-loss coherent RF photonic signal distribution. Despite these superior advances, reported photonics-assisted radars typically rely on sophisticated and expensive electronic devices such as arbitrary waveform generators (AWGs) and tunable high-frequency oscillators.[19–22]
Figure 1. Schematic architecture of the proposed photonic wideband stepped-frequency (P-WSF) radar system driven by MHz-speed electronics only for target ranging and sensing. The photonic radar system consists of several key building blocks, including a photonics-based radar signal generator, a photonic signal demodulation unit, O/E, and E/O converters, and microwave antennas. An electronic oscillator that oscillates at a frequency in the level of MHz (see inset (i)), is driving the photonics-based signal generator to produce stepped-frequency (SF) signals in the optical domain, of which the center frequency progressively shifts at a fixed step. Through O/E conversion, microwave SF signals (see inset (ii)) is generated and then be transmitted by a microwave antenna. The returned radar signals collected by a receiver antenna are mixed with a photonic reference signal, producing a demodulated electric signal in the baseband. Distance and velocity information of objects of interest, such as unmanned aerial vehicles, can be extracted from the demodulated signal, using low-speed digital signal processing. O/E, optical-to-electrical conversion; E/O, electrical-to-optical conversion; DSP, digital signal processing.

The use of these benchtop high-frequency electronic devices, for example, ultra-fast AWGs, in turn, sets the upper limit for achievable radar signal bandwidth, and hinders the translation of demonstrated radar systems to practical applications from laboratories. Optical frequency doubling or quadrupling and photonic digital-to-analog converters have been used to fold the bandwidth requirement by half or a quarter, however, at the cost of modulator bias instability, additional complexity, unavoidable frequency spurs, and limited agility. Alternative approaches based on frequency-sweeping light sources, laser pulse shaping, and chirped optoelectronic oscillators also have attracted great interest; however, for these techniques, it remains challenging to simultaneously meet key requirements of high frequency–time linearity for accurate ranging, wide bandwidth for high detection resolution, and long pulse duration for precisely capturing kinetic targets. Therefore, an MHz-level electronics-driven photonic analog radar system that can simultaneously achieve high spatial resolution enabled by broad bandwidth, real-time detection, and high frequency–time linearity is highly desirable for practical radar applications.

Here we demonstrate a photonic wideband stepped-frequency radar (P-WSF) system that provides >11 GHz bandwidth radar signals operated at a center frequency of 34 GHz (in Ka-band), driven by MHz-level electronics only at a speed of only tens of MHz. This broadband P-WSF can eliminate the need of high-speed and complicated electronics for implementing wideband radars. The P-WSF radar leverages analog photonic generation and processing of ultra-wideband signals using only MHz-level electronics for detection and imaging. Specifically, stepped-frequency (SF) continuous wave radar signals are synthesized using a frequency-shifted optical modulation driven by a low-frequency electronic oscillator (40/80 MHz in this work), synthesizing a signal bandwidth of more than 11 GHz (exceeding 20 GHz without RF antenna bandwidth limitation). The optical mixing of such broadband radar signal and its echoes at the receiver, produces a demodulated signal with a bandwidth of much less than the frequency step, which can be easily processed by low-bandwidth ADCs with high precision, allowing for real-time radar ranging and imaging. We demonstrate, for the first time, a flexible photonic radar system for range detection and 2D imaging of moving targets and an unmanned aerial vehicle (UAV) with a high spatial resolution down to 1.3 cm, and an ultra-large time-bandwidth product exceeding 5 x 10^5 using only MHz-speed electronics, which yields a figure of merit improvement exceeding one order of magnitude compared to state of the art relying on using GHz-speed electronics. The demonstration of such a P-WSF radar opens a new way to implement high-performance radars using only MHz electronics for wideband radar signal generation and processing, which relaxes the hardware burden and complexity conventionally required in electronic radars.

2. Concept and Implementation of the P-WSF Radar System

The conceptual diagram of the proposed P-WSF radar is illustrated in Figure 1. The photonic radar system is composed of key building blocks, including a photonic signal generator that produces ultra-wideband photonic radar signals, an optical-to-electrical (O/E) converter that translates the photonic signals to microwave signals, RF antennas, a photonic-based signal mixing unit that enables signal demodulation in the optical domain, and an electrical-to-optical converter for electric signal processing. An electronic oscillator that oscillates at an MHz-level RF
Figure 2. Experimental setup of the P-WSF radar for ranging and imaging applications. a) The proposed photonics-based SF radar platform consists of a radar transmitter that optically generates broadband RF signals, driven by an MHz-frequency electrical oscillator and a radar receiver that provides optical signal mixing to form baseband demodulated electrical signals through photodetection. b) Schematic illustrations of temporal waveforms at different locations (i–iii) of the radar transmitter. c) Schematic illustration of returned radar signals at different locations (iv–vi) of the radar receiver. LD: laser diode; Mod: optical switch; Osc: electronic oscillator; OC: optical coupler; AOM: acousto-optic modulator; ISO, optical isolator; EDFA: erbium-doped fiber amplifier; OBPF: optical bandpass filter; PD: photodiode; PA: power amplifier; LNA: low-noise amplifier; PM: phase modulator.

The experimental implementation of the P-WSF radar is shown in Figure 2a, which comprises a transmitter unit, a receiver unit, and two RF horn antennas for radar signal emission and collection. The schematic illustrations of signals at different locations (indicated by marks (i–vi)) in the radar transmitter and the receiver are shown in Figure 2b,c, respectively. In the radar transmitter, a continuous-wave laser (LD1) centered at a frequency of $f_c$ is chopped into a train of rectangular pulses with a pulse duration of $\tau_p$ and a repetition rate of $f_p$ using an optical switch driven by an electronic pulsed signal generator. A 10% tap of the seed pulses is injected to a fiber-based optical frequency-shifted cavity through an optical coupler (OC1), in which an acousto-optic modulator (AOM) is used to progressively shift the pulse center frequency by a fixed frequency step. The frequency shift $\Delta f$ can be positive or negative, depending on the frequency shift direction of the AOM. The absolute frequency shift $|\Delta f|$ is defined by a low-frequency electronic oscillator, which is set to 40/80 MHz in the following experimental demonstrations. Here we illustrate the principle of the P-WSF radar based on a positive frequency-shifting modulation for the sake of clarity (see detailed mathematical derivations in Note S1, Supporting Information). After $n$-time circulations in the optical loop, the light frequency is shifted to $f_c + n \times \Delta f$, where $n = 1, 2, 3 \ldots N$, forming an optical SF signal, as illustrated by the waveform at Location (ii) in Figure 2b. Each seed pulse duration $\tau_p$ is controlled to be equal to or slightly less than the transient time $\tau_c$ of one recirculation in the cavity, in order to avoid interference due to the overlap between two adjacent pulses. Inside the cavity, an optical isolator is used to determine the light circulating direction (clockwise) and an erbium-doped fiber amplifier (EDFA) is utilized to compensate for the optical losses. An optical bandpass filter (OBPF1)
is used to define the spectral range of the frequency-shifted optical signal and reduce amplifier noise. A 10% tap of optical SF signal is combined with a local optical oscillator at \( f_{LO} \) in a photodetector via heterodyne detection, producing SF signal in the microwave domain with an instantaneous frequency of \( f_c = [f_c - f_{LO} + n \times \Delta f] \) and a total bandwidth of \( N \times \Delta f \) (Location (iii)). An ultra-wideband signal can be generated when the circulation number \( N \) is set to a large value defined by the bandwidth of OBPF1, forming the basis of wideband radar signal generation. The microwave SF signal is amplified before being emitted by a horn antenna. It is worth mentioning that the RF carrier frequency can be flexibly tuned by changing the frequency difference between the two lasers, enabling the potential to achieve frequency-agile capability for multi-band operation.

In the radar receiver, radar signals reflected by targets are collected by a microwave horn antenna before being amplified and optically processed, as shown in Figure 2a. Compared to the emitted radar signal, the reflected radar signal shows a time delay \( \tau \), as illustrated by the waveform at Location (iv) in Figure 2c. The time delay is stemmed from the round-trip flying time \( \tau = 2d/c \) over the distance \( d \) between the antennas and the object, where \( c \) is the light speed in the air. Due to the time delay, each frequency-shifted pulse picks up a different phase shift \( \Delta \phi = (n\Delta f) \times \tau \). This frequency-dependent phase shift forms the basis of extracting the distance information of the object, since the distance \( d \) can be retrieved once the phase shift is acquired. In order to convert the time-varying phase shift to a measurable property, an optical phase modulator is used to mix the returned radar signal with the reference signal, which consequently allows for translating the phase shift to directly measurable intensity variation. Via phase modulating the optical local oscillation frequency \( f_{LO} \), one of the first-order sidebands is generated at frequency range from \( f_c + \Delta f \) to \( f_c + N\Delta f \), which falls in the same spectral range as the optical SF signal. However, these two overlapped spectral components have a phase difference dictated by \( \Delta \phi \). An optical bandpass filter (OBPF2) is utilized to select the spectrally overlapped signals and remove spurs at other frequencies. As results, the interference of these two spectrally overlapped signals translates the frequency-dependent phase difference to a time-varying amplitude envelope proportional to \( \cos[\Pi(t) \times 2\pi n\Delta f \tau] \), where \( \Pi(t) \) represents a train of frequency-shifted rectangular pulse, as illustrated by the waveform at Location (v) in Figure 2c. Via photodetection in PD2, the demodulated optical signal is converted to electrical signals in the baseband with an instantaneous bandwidth much smaller than \( \Delta f \), which can be rapidly processed by electronics with high precision. By applying an inverse Fourier transformation (IFFT) to the detected electrical signal, the time delay \( \tau \) and thus the object distance \( d \) can be obtained from the IFFT spectrum (Note S1, Supporting Information). It is worth mentioning that the phase relationship between two adjacent frequencies is fixed due to the physical length of the fiber used in the loop.

3. Synthesizing Ultra-Broadband Radar Signals for High-Resolution Ranging

Broadband radar signals with flexible bandwidth tunability are critical to applications where high-spatial resolution and multiband operation are desirable, which is challenging and complicated in conventional electronic radars. Here we experimentally demonstrate a flexible tuning of radar signal bandwidth in the proposed P-WSF radar system, achieving an RF bandwidth beyond 11.52 GHz and thus centimeter-level spatial resolution, based on the setup shown in Figure 2a. Details about experimental setup and parameters can be found in Notes S2 and S3, Supporting Information.

3.1. Radar Signal Generation with \( \geq 10 \) GHz Bandwidth and Ultra-High Frequency–Time Linearity

Figure 3 shows the temporal waveforms of microwave SF radar signals with various bandwidths measured at Location (iii) in Figure 2a. These measured microwave waveforms are converted to baseband frequencies for observation, using a self-heterodyne mixing of the photonic SF signal and a CW signal split from LD1. Figure 3a shows the temporal and instantaneous frequency of a periodic SF signal with a bandwidth of 5.76 GHz and a temporal length of 25 μs. The achieved bandwidth is determined by the passband bandwidth of OBPF1, and the decaying envelop at the pulse train tail is attributed to the roll-off response of the filter edge. Each period of the recurring SF signals consists of 72 frequency-shifted sub-pulses with a frequency step of 80 MHz, resulting in a total bandwidth of 5.76 GHz. Figure 3b shows the zoomed-in waveform and corresponding instantaneous frequency of the first four sub-pulses, in which the dashed red trace illustrates the envelope of the seed pulse generated by a function generator (PSG) with a duration \( \tau_c \) of 340 ns (full width at half maximum) and a repetition rate \( f_p \) of 40 kHz (25 μs period interval). Figure 3b clearly indicates that the carrier frequency of the SF waveforms progressively and constantly increases as a function of time, which is verified by the frequency–time image obtained by short-term Fourier transform (STFT). In this demonstration, the optical loop length in the radar transmitter was set to have a round-trip time of \( \approx 340 \) ns to match the pulse length of each frequency-shifted sub-pulse. Through detuning \( f_{LO} \), a 5.76-GHz-wide SF signal starting from 28 GHz is synthesized in the microwave domain (Note S4, Supporting Information).

The synthesized bandwidth of microwave SF signals can be flexibly broadened, by increasing the passband bandwidth of OBPF1 in the optical loop illustrated in Figure 2a. In demonstrations, the temporal duration \( \tau_c \) (≈ 340 ns) of the seed pulse and the optical loop length (≈ 70 m long single-mode optical fiber) were kept constant throughout the demonstrations. In order to accommodate increased numbers of frequency-shifted pulses in the time domain, the seed pulse frequency was increased to 40 and 50 μs (corresponding to repetition rates \( 1/f_p \) of 25 and 20 kHz), respectively. These increased pulse intervals allow to achieve enhanced bandwidths of 9.2 GHz (115 sub-pulses) and 11.52 GHz (144 pulses), as shown in Figure 3c,e, separately. The zoomed-in temporal waveforms and instantaneous frequencies indicate the center frequency of the sub-pulses consecutively hops by a fixed frequency step of 80 MHz, while the adjacent sub-pulses maintain a relatively stable amplitude. The 11.52-GHz-wide SF signal with a long pulse duration of 50 μs leads to an ultra-large time–bandwidth product of \( 5.76 \times 10^5 \), outperforming most of the reported photonics-based radars, as shown in Table 1. The radar
Figure 3. Demonstration of flexible tuning of radar signal bandwidth from 5.76 to 11.52 GHz. The temporal waveforms are obtained through a self-heterodyne process between the generated SF signals and the seed laser LD1. a,c,e) The temporal waveforms and the corresponding time-frequency mapping of radar pulses with a duration of 25, 40, and 50 μs, respectively. These pulse lengths translate to radar signal bandwidths of 5.76, 9.20, and 11.52 GHz, respectively. b,d,f) The zoomed-in view of the temporal waveforms and corresponding time–frequency relations, obtained by short-term Fourier transform results (STFT). I.F., instantaneous frequency.

Table 1. Comparison of state-of-the-art photonics-based radar systems. BW: bandwidth; CF: center frequency; TBP: time–bandwidth product; RDS: RF device speed; FoM: figure of merits; ADC: analog-to-digital converter; AWG: arbitrary waveform generator; RR: range resolution; LO: local oscillator. For the FoM comparison, sampling rates of ADCs is mapped to its corresponding maximum Nyquist frequencies. The RDS for signal processing is marked by \( R_x \) and for signal generation is marked by \( R_x \).

| Ref.  | BW [GHz] | CF [GHz] | TBP \( \times 10^3 \) | RDS for signal generation/processing | RR [cm] | FoM TBP/RDS \( \times 10^3 \) GHz\(^{-1} \) |
|-------|----------|----------|-----------------|-------------------------------------|--------|-----------------------------|
| [13]  | 30       | 85       | 0.6             | 40 Gs s\(^{-1}\) (ADC)\(^{th}\)     | 0.39   | 0.03                        |
| [22]  | 18.2     | 26       | 540             | 65 Gs s\(^{-1}\) (DAC)\(^{th}\)     | 0.82   | 16.6                        |
| [33]  | 7.5      | 6.85     | 80              | >15 GHz Gs s\(^{-1}\) (ADC)\(^{th}\) | 1.05   | 10.7                        |
| [34]  | 0.6      | 7.3      | 300             | 7.15–7.45 GHz (AWG)\(^{th}\)        | 25     | 40.3                        |
| [14]  | 8        | 22       | 40              | 4.5–6.5 GHz (AWG)\(^{th}\)          | 2      | 6.15                        |
| [35]  | 12       | 34       | 2,400           | 7–10 GHz (AWG)\(^{th}\)             | 1.3    | 240                         |
| [36]  | 8        | 94       | 79.2            | 0–12.5 GHz (AWG)\(^{th}\)           | 1.9    | 6.3                         |
| [37]  | 8        | 22       | 79.2            | 9–13 GHz (AWG)\(^{th}\)             | 1.9    | 6.1                         |
| This work | >11 GHz | 32       | 576             | 40/80 MHz (LO)\(^{th}\)             | 1.3(0.75) | 7200                        |
Figure 4. Demonstration of high-resolution radar ranging. a) Schematic of the experimental setup for radar ranging demonstration. Plane reflectors with a size of 2.5 cm × 6 cm separated by adjustable separation are placed within the radar beam to evaluate the achievable spatial resolution. b) The temporal waveforms of detected demodulated electrical signals in the presence of none, one, and two reflectors, respectively. c) The corresponding ranging results obtained by inverse fast Fourier transform (IFFT). d–f) Experimental ranging results of the two reflectors separated at 3 cm using radar bandwidths of 5.76, 9.20, and 11.52 GHz, respectively. g–i) Experimental ranging results of the two reflectors separated at 1.5 cm using radar bandwidths of 5.76, 9.20, and 11.52 GHz, respectively.

Signal can be easily scaled up beyond 20 GHz by extending the bandwidth of the optical filter (Note S5, Supporting Information), while maintaining excellent linearity. In the following experiments, we focus on the demonstration based on 11.52 GHz bandwidth, considering the available operation bandwidth of the microwave antennas during experiments. The P-WSF radar with such a high time–bandwidth product will enable an ultra-fine spatial resolution and velocity resolution, based on the fact that the radar signals simultaneously have a large bandwidth and a wide time width. Moreover, the radar bandwidth can also be tuned by adjusting the oscillation frequency of the electrical oscillator (Note S5, Supporting Information).

3.2. Centimeter-Resolution Radar Ranging

We perform proof-of-concept demonstrations of high-resolution radar ranging using the generated broadband microwave SF signals. Figure 4a illustrates the diagram of the experimental configuration for radar ranging demonstrations, in which one or two reflectors are placed to emulate targets of interest (Note S6, Supporting Information). Figure 4b shows one period of the demodulated electrical signals detected by the receiver photodetector in the presence of none, one, and two reflectors, respectively. The amplitudes of the rectangular pulses in each trace manifest as the relative phase shifts received by the frequency-shifted subpulses, owing to the signal flying time r between the objects and radar antennas, based on the operational principle illustrated in Figure 2. The time-dependent phase information is digitally sampled and then processed to map out the corresponding time delay and thus the distance. In the absence of objects, the trace in blue shows a nearly uniform amplitude envelope, indicating that no returned radar signal is detected; this leads to a nondetectable ranging signal obtained from fast Fourier transform (IFFT) of the temporal signal, as shown in Figure 4c.

In contrast, when in the presence of a single reflector, the demodulated signal shows a periodic modulation in amplitude, which is translated to a dominant peak in the distance space via IFFT (Notes S1 and S7, Supporting Information), as shown in Figure 4c. Furthermore, when we place two reflectors 3-cm apart, the electrical signal shows a more complex modulation in pulse amplitude, resulting in two closely spaced peaks in Figure 4c. It
should be noted that the two reflectors cannot be clearly identified due to the limited radar signal bandwidth of ≈4.8 GHz in the demonstration. This can be understood from the perspective of the Fourier transform theorem: more sampling points (number of pulses and thus bandwidth) are desirable to achieve a finer spectral resolution in the Fourier space (accordingly, the spatial resolution in the range). It is important to note that the signal processing only requires a low sampling rate of >2.9 MSa s\(^{-1}\), since the demodulated sub-pulses have a repetition rate of ≈2.9 MHz (the inverse of the round-trip time of the optical loop). Using an increased seed pulse duration can further reduce the required sampling rate under MSa s\(^{-1}\) level, which can greatly relax the workload for digital signal processing. In the proof-of-concept demonstrations, we used a real-time electrical oscilloscope operated at a sampling rate of 31.25 MSa s\(^{-1}\) for data acquisition. Thus, the P-WSF radar has a great potential to enable fast and even real-time radar ranging capability, since the data acquisition and processing can be well handled by low-speed electronics.

Next, we demonstrate that finer spatial resolutions are achieved using increased radar bandwidth. Figure 4d–f show the ranging results of the P-WSF radar with varied signal bandwidths of 5.76, 9.20, and 11.52 GHz, respectively, when two plane reflectors separated by 3 cm. This 3-cm separation can be well identified by the P-WSF radar operated with these three bandwidths; however, the demonstration using 11.52 GHz-wide bandwidth (from 28 to 39.52 GHz) shows a much finer ranging resolution compared to the other two cases. When the separation is decreased to 1.5 cm, only the radar with 11.52 GHz bandwidth can distinguish this reduced spatial gap, as shown in Figure 4g–i. This difference can be understood by examining the corresponding theoretical ranging resolutions; 11.52 GHz bandwidth allows for a theoretical spatial resolution of 1.3 cm given by \(c/(2N \times \Delta f)\), while 5.72 and 9.20 GHz bandwidths have a ranging resolution of 2.6 and 1.6 cm, respectively. The radar signal can be easily scaled up to exceed 20 GHz (corresponding to a spatial resolution of 0.75 cm) by extending the bandwidth of the optical filter (Note S4, Supporting Information). It is worth mentioning that no windowing function was applied in digital signal processing at the receiver. From experimental explorations, we found that using polarization-maintaining components can suppress the gain fluctuation caused by polarization scrambling in the optical loop, which can reduce the inter-pulse amplitude fluctuations and improve the signal SNR.

4. Centimeter-Resolution 2D Radar Imaging

The P-WSF radar system is capable of realizing 2D imaging of kinetic objects, which is an attractive capability for target identification in radar applications. The 2D imaging is achieved by adding a Doppler dimension that measures the velocity of the moving objects, which is termed as a cross-range dimension. The object movements can be captured by multiple consecutive microwave SF pulses, each of which can record the instantaneous distances, as well as the Doppler frequency shift caused by objects’ movement. After signal processing using 2D Fourier transform (Notes S1 and S7, Supporting Information), 2D images of moving targets that contain the range and cross-range dimensions can be reconstructed, based on the principle of inverse synthetic aperture radars (ISARs).[40]

4.1. ISAR Imaging of Kinetic Objects

Figure 5a illustrates the experimental setup for demonstrating 2D radar imaging. Three cylindrical objects (top view) with a radius of 3 cm and a height of 4 cm were mounted on a rotating platform to emulate dynamically moving objects. Three objects are placed in a nonsymmetric arrangement for unambiguous rotation angle identification. The rotating platform is located ≈1.52 m away from radar antennas that transmit and receive 11.52 GHz-wide radar pulses. The platform rotates at an angular speed of ≈50 rad s\(^{-1}\) clockwise, corresponding to ≈477 revolutions per min (RPM). Figure 5b shows the side view and the inclined view of objects under test; microwave absorbers are used to avoid reflections and interference from the ambient environment. Figure 5c–h show the constructed images of the moving objects at different rotational angles covering the entire 360 degrees. In Figure 5c–h, three moving objects can be distinguished with high resolutions, which agrees well with their expected locations indicated by dashed circles. It should be noted that the lower detected amplitude of the object located at the edge of the radar view range is caused by the 8-degree view angle of the antennas with high beam directionality in an indoor measurement condition. This phenomenon will be mitigated using antennas with larger beam angles or outdoor measurements with increased object distance.

Each radar 2D imaging frame shown in Figure 5c–h are constructed from 100 consecutive returned radar SF pulses, corresponding to a viewing time of 5 ms (100×50 μs). Since the resolution for the Doppler frequency shift is the inverse of the viewing time,[40] the 11.52-GHz-wideband P-WSF radar has a Doppler resolution of 200 Hz, corresponding to a radial velocity resolution of 1 m s\(^{-1}\) when the radar center frequency is 34 GHz. Owing to the shot view time of 5 ms, the P-WSF radar imaging is ideally able to achieve a high refresh rate of 200 frames per s (FPS). Such a high FPS is extremely attractive for imaging fast-moving objects in real-time, since the data acquisition and processing only requires low-speed electronic processors. However, in the current implementation, the refresh rate is limited by the unoptimized data transfer process and data computation for fast Fourier transform. It should be noted that a higher frame rate can be achieved by deploying a continuously moving time window by one period, rather than discretely truncating 100 periods of SF pulses.

4.2. ISAR Imaging of an Unmanned Aerial Vehicle (UAV)

As an application example of the P-WSF radar, we demonstrate the 2D imaging of an unmanned aerial vehicle (UAV) by resolving the fast-spinning propellers. For safety and regulation considerations, we performed the demonstration in a lab environment; we mounted a commercial UAV (Zero-X Banshee) on a holder to emulate a hovering UAV under detection with rapidly rotating blades with a width varying from 1.2 to 1.9 cm Figure 6a shows the experimental configuration for radar imaging of a UAV, with a radar signal bandwidth of 11.52 GHz. During the experiment, we focus on the imaging of the two propellers of the drone within the viewing angle of the P-WSF radar, as shown by Figure 6b. The drone was slightly tilted in the vertical direction, in order to avoid shielding the returned radar signal from the farther blades.

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Figure 5. Demonstration of high-resolution radar imaging. a) Schematic of the experimental setup for radar imaging demonstration. Three cylinders with a radius of 3 cm and a height of 4 cm mounted on a rotating plate to demonstrate the imaging capability of moving objects. b) The side view and the inclined view of the moving objects, respectively. Microwave absorbers with artificial structures are used to shield reflections from the ambient environment. c–h) Reconstructed 2D images of the moving object at various angles. Dashed circles indicate the expected locations of objects of interest.

Figure 6c–e show the reconstructed images of rapidly moving blades with a rotation speed of 7500 degree s\(^{-1}\) (corresponding to 1250 RPM), in which the expected blade orientation is outlined by dashed envelopes. Each radar imaging result is retrieved using 60 consecutive microwave SF pulses. The blades of the UAV can be resolved by recognizing the envelope from the retrieved image; however, the imaging quality is limited by the low reflection cross-section of the narrow blades, and twisted blade planes reduce the strength of returned radar signals to the radar receiver. In the experiment, an aluminum coating was used to increase the reflectivity in the demonstration. Figure 6d shows the radar imaging result of a propeller with its blade tip pointing to the radar antennas, which has a lower imaging SNR due to the minimum reflection cross-section. The intensity variation of the imaging results in Figure 6e is attributed to the rotational motion of the blade, compared to the result in Figure 6e. The background spurs in Figure 6c–e are caused by stationery reflection from the drone body. The antennas (from L3 Harris Corp.) used in this manuscript have high RF beam directivity with a narrow horizontal beamwidth around 18 cm at 1.4 m (beam angle of 8–10 degrees), insufficient to cover the area of four propellers with a horizontal separation around 40 cm. Broader imaging view angles can be achieved using well-established approaches, such as smaller horn antennas, RF beam scanning, and additive receiving antennas. This application example of P-WSF radar in UAV detection shows a great potential to detect and identify rapid moving targets with centimeter-level resolution in real-world applications.

The demonstrated P-WSF radar leverages analog photonic generation and processing of ultra-wideband signals using only MHz-level electronics, allowing for real-time radar ranging and imaging using low-bandwidth and high-precision ADCs. Here, we introduce a providing a figure of merit to compare the overall performance between our demonstrated radars with reported schemes, which clearly shows the outperforming advantages of the achieved ultra-large time-bandwidth product using only MHz-speed electronics (see Table 1).

5. Discussion and Conclusion

The P-WSF radar system driven by MHz-level electronics has demonstrated a tunable bandwidth up to 11.52 GHz, enabling centimeter spatial resolution for ranging and imaging. The SF radar signal bandwidth can be further extended to achieve tens
of GHz and exceed 100 GHz bandwidth to radically compete and exceed the capability of high-speed electronics by broadening the bandpass filter bandwidth and increasing the number of frequency-shifted sub-pulses. However, the accumulated optical amplifier noise during light recirculation limits the maximum achievable number of frequency-shifted pulses; as a result, the signal-to-noise ratio of the frequency-shifted pulses degrades progressively after many round trips. Alternatively, a promising approach to achieving a much broader bandwidth without affecting the ranging performance is using a parallel frequency-shifted scheme in which multiple (M) seed pulses with different carrier frequencies (e.g., frequency combs) are frequency shifted at the same time, and the resultant multiple SF signals are concatenated in the microwave domain via spectrum stitching. This approach has the potential to enlarge the P-WSF radar bandwidth by M times.

In future developments, the radar systems can be feasibly simplified and miniaturized using a miniature EDFA and replacing the bulky optical tunable filter. Specifically, the use of compact optical filters based on fiber Bragg gratings or electrically gating the on–off state of the AOM in the optical loop can practically replace the bulky and costly tunable optical filters, achieving desirable bandwidth tuning flexibility and sharper roll-offs. We observed an SNR of 17 dB for the SF radar transmitter, which is sufficient for near-range applications under a safe transmitting RF power such as hand gesture recognition,\textsuperscript{42} fall detection,\textsuperscript{43} and industrial quality inspection.\textsuperscript{44} Indeed, a further increase in SNR is favored for improved ranging accuracy (Note S6, Supporting Information). One way to increase the signal’s SNR is using polarization-maintaining components to suppress the environmental-dependent polarization scrambling to achieve a stable sub-pulse amplitude and a broader synthesized bandwidth.

Radar waveforms based on linear frequency modulation (LFM) and SF modulation are both widely used, while possessing fundamental differences in mapping the round-trip time of flight for range detection. The LFM radar encodes the range information (time delay of the detecting signal’s round-trip, $r$) onto a new oscillating frequency $f_{\text{chirp}} = kr$, proportional to the chirp rate $k = bw/T$, where $bw$ is the bandwidth and $T$ is the chirp repetition rate. The SF radar maps the time delay onto phase changes Equation (9) in the Supporting Information. Compared with the LFM radars based on continuously chirped signals, SF radar based on discretely frequency steps, has a smaller unambiguous range ($\approx 100$ m commercially\textsuperscript{45}), constrained by the step frequency $\Delta f$. Therefore, SF radars can be a complementary approach for near-range practical applications, with the benefits of high resolutions and a lower sampling speed. Furthermore, SF radars require a phase-sensitive coherent receiver for an improved detection performance at the cost of increased complexity in signal processing and demodulation.

The SF radar’s unambiguous range can be enlarged using smaller frequency steps (Note S5, Supporting Information). In practical implementation, the frequency step is set by the operating frequency of the AOM, typically in the range of a few MHz to 100s MHz, corresponding to an unambiguous range spanning from a few meters to $> 100$ m. For example, a commercially available AOM operated at 5.5 MHz (Brimrose, AMF-55-1.3) enables an unambiguous range of around 30 m. A feasible alternative approach to extending the unambiguous range is to utilize the differential frequency of two AOMs with opposite frequency shifts (one positive and one negative), producing a sub-MHz frequency shift corresponding to an unambiguous range exceeding 150 m. In this work, we have shown an experimental demonstration of an increased unambiguous range by a factor of two by reducing the frequency step from 80 to 40 MHz. The demonstration of a
Further smaller frequency step was not performed due to the lack of AOMs operated at lower frequencies in our lab, which is, however, out of the scope of this work and will be investigated in the future development. It is straightforward and entirely feasible to increase the loop delay using a compact optical fiber coil with extended length, with negligible effects from the dispersion and optical nonlinearity due to the long (μs-level) optical pulses with low peak power. Therefore, the loop length is not a practical limitation for the proposed radar. As shown in Figure S2, Supporting Information in Note S3, Supporting Information, we have demonstrated two different loop delays, that is, 150 and 340 ns, corresponding to unambiguous ranges of 22.5 and 50 m, respectively, as a proof-of-concept demonstration. Alternatively, a hybrid radar scheme can be used in which an auxiliary radar can identify the range zone to assist P-WSF radar’s high-resolution detection. Although the unambiguous range in the current demonstration is limited, the demonstrated P-WSF radar system addresses near-range applications such as autonomous pilot, gesture movement recognition, and penetrating detection.

The P-WSF radar system has a comparable performance with the photonic radars based on high-speed digital microwave frequency synthesizer, for example, using AWG, in terms of ranging resolution, signal-to-noise ratio (SNR), and imaging quality (Notes S8 and S9, Supporting Information). These comparisons indicate that the P-WSF radar can yield comparable ranging and imaging performance due to the achieved broad radar bandwidth and the efficient frequency-shifted modulation, while it significantly relaxes the requirements of high-speed digital electronics for signal generation and processing. Thus, the P-WSF radar system can integrate attractive advantages, such as high resolution, rapid signal generation and processing, low system complexity and cost, and flexible tunability. It should be noted that in the proof-of-concept demonstrations, two lasers (LD1 and LD2) are not phase-locked, which contributes to increased phase noise. In order to further improve the SNR, two injection-locked lasers or coherent light sources such as stabilized optical frequency combs can be deployed to reduce the noise in the heterodyne signal mixing via photodetection. For the future development toward the miniaturization of the P-WSF radar system, recent advances in photonic integration of key functional units such as on-chip acousto-optic frequency shifters \(^{(46)}\) and versatile integrated optical passband filters \(^{(47)}\) with sharp spectral roll-off provide an important and promising technical basis for achieving compact P-WSF radars. We would like to note that a microwave photonic radar using optical frequency shifting modulation of linearly chirp waveform generated by an ultra-high-speed benchtop arbitrary electric waveform generator and an intricately configured high-speed electro-optic modulator was reported, \(^{(42)}\) based on a fundamentally different principle and configurations. This scheme was realized at the costs of high configuration complexity, modulator bias stability, GHz-level frequency step (thus centimeter-level unambiguous range) and digital arbitrary waveform generator, which might exhibit limitations in applications.

In summary, we demonstrate a photonic ultra-wideband step-frequency radar with a bandwidth up to 11.52 GHz, driven by MHz-level electronics. This P-WSF radar, for the first time, simultaneously combines the high spatial and velocity resolution enabled by ultra-wide radar bandwidth and the rapid radar detection due to the low demodulation processing bandwidth. Based on these superior features, high-resolution radar ranging and 2D radar imaging of reflectors and a commercial unmanned aerial vehicle are demonstrated. This novel photonic radar offers a new path toward high-resolution, rapid-response, and low-cost radar modules with reduced system complexity for demanding practical applications, including autopilot assistance, gesture identification, environmental sensing, and medical imaging applications.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Author Contributions
Y.L. and Z.Z. contributed equally to this work. Y.L. conceived the idea and research project; Y.L. and Z.Z. designed system architecture; Z.Z. and Y.L. performed experimental demonstration, data processing, and results analysis; Y.L. and Z.Z. wrote the manuscript with inputs and discussions from M.B. and B.J.E.; Y.L. and B.J.E. supervised the project.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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acousto-optics, microwave photonics, radar ranging and imaging, wide-band RF signal generation

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