Demonstration of ultra-high-resolution photonics-based Ka-band inverse synthetic aperture radar imaging

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Abstract: We demonstrate a photonics-based Ka-band radar system with 12 GHz bandwidth by optical signal generation and de-chirp processing. Inverse synthetic aperture radar imaging with a range resolution as high as ~1.3 cm high-resolution is achieved. © 2018 The Author(s)

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1. Introduction

High-resolution target detection and real-time radar imaging have wide applications in many different areas [1, 2]. Inverse synthetic aperture radar (ISAR) can achieve high-resolution radar images, whose imaging depends on the rotation of the targets [3]. In order to realize high-resolution and real-time ISAR imaging, it is necessary to have a large bandwidth transmit signal and fast digital processing [4]. In conventional electrical radar, due to the limited bandwidth of the electronic devices, signal generation by a direct digital synthesizer (DDS) is limited to a few gigahertz. As the bandwidth increases, the analog to digital converters (ADCs) would cause quantization distortion and spurious increment. Therefore, the resolution of the receiver and the performance of the radar are restricted. Thanks to the advantages of ultra-wide bandwidth and low transmission loss, microwave photonic technologies have been proposed to solve these problems [5, 6]. Linear frequency modulated continuous-wave (LFMCW) radar has very high resolution and ranging accuracy. Through de-chirping of the received LFM signals, fast or even real-time imaging can be realized [2]. In [7], we have demonstrated a photonics-based K-band radar with an 8-GHz bandwidth (18-26GHz) by microwave photonic frequency multiplication in the transmitter and microwave photonic frequency mixing in the receiver. Based on this system, ISAR imaging with a 2-dimensional resolution as high as ~2 cm × ~2 cm is achieved. The prominent advantage of this system is the ultra-large operation bandwidth and the real-time imaging capability. The potential bandwidth of a photonics-based radar system can reach tens of GHz, which, however, has not been fully developed in the system in [7]. Therefore, we can further improve the radar resolution by increasing the signal bandwidth.

In this report, we put forward the operation bandwidth of the photonics-based radar to recorded high level in the frequency bands below 40 GHz. The established photonics-based radar has a bandwidth of 12 GHz (28-40 GHz), which covers nearly the whole Ka-band. In the receiver, the de-chirped signal is sampled with an ADC working at 2.5 MSa/s. Range resolution of this Ka-band radar is demonstrated to be ~1.3 cm. ISAR imaging of a small airplane model is demonstrated.

2. Principle

Fig.1 shows the setup of the photonics-based ISAR system. A continuous-wave (CW) light from a laser diode (LD) is modulated by a dual-parallel Mach-Zehnder modulator (DPMZM), which is driven by an intermediate frequency (IF) band linear frequency modulated continuous-wave (LFMCW) signal generated by a low-speed electrical signal generator. The IF-LFMCW signal passes through an electrical 90° hybrid coupler. The two output signals are applied to the two RF ports of the DPMZM. After properly setting the bias voltages, the DPMZM works at frequency quadrupling mode [8], i.e., only the ±2nd-order modulation sidebands are generated. Then, the optical signal is equally split into two branches by an optical coupler (OC). The signal in the lower branch is used as a reference for de-chirping the radar echoes. In the upper branch, the optical signal is sent to a photodetector (PD1) to perform optical-to-electrical conversion. After PD1, an LFMCW signal is generated, of which the frequency and bandwidth are quadrupled as compared with the original IF-LFMCW signal. The generated LFMCW signal is amplified by an electrical amplifier (EA1) before emitting to the free space through a transmit antenna (Tx) for ISAR imaging. The echoes reflected from the targets are collected by a receive antenna (Rx), and properly amplified by another electrical amplifier (EA2) before applied to an electro-optical phase modulator (PM) to modulate the reference optical signal, which can be treated as two frequency-sweeping optical carriers. After the PM, at a given time, the 1st-order sideband generated by phase modulation of the first optical carrier would be located closely to the second optical carrier in the spectrum. Then, an optical bandpass filter (OBPF) is used to select out this 1st-order
phase modulation sideband and the second optical carrier. The obtained optical signal is sent to another photodetector (PD2) to perform photonic frequency mixing. After PD2, an electrical low-pass filter (ELPF) with a proper bandwidth is used to remove the high-frequency interference. To this point, de-chirping of the received LFM signal is completed. The de-chirped signal after the ELPF has a frequency of $\Delta f = k \Delta \tau$, where $k$ is the chirp rate of the transmitted LFMCW signal, and $\Delta \tau$ is the time delay of the echo signal compared with the transmitted LFMCW signal. By properly setting the chirp rate of the transmitted LFMCW signal according to the detection range, the signal after de-chirping can be controlled to a low frequency, and it can be digitalized by a low-speed ADC with a high precision. The digitized signal can be processed in a digital signal processing (DSP) unit based on mature ISAR imaging algorithms.

![Schematic diagram of the photonics-based radar](image)

**Fig. 1.** Schematic diagram of the photonics-based radar. LD: laser diode; OC: optical coupler; DPMZM: dual-parallel Mach-Zehnder modulator; PD: photo-detector; PM: phase modulator; OBPF: optical band-pass filter; ELPF: electrical low-pass filter; ADC: analog-to-digital converter; DSP: digital signal processing.

### 3. Experimental demonstration

Based on the setup in Fig. 1, a Ka-band radar is established. The electrical IF-LFMCW signal applied to the DPMZM has a bandwidth of 3 GHz (7-10 GHz) and a repetition rate of 5 kHz. The generated LFM signal covers from 28 GHz to 40 GHz with a bandwidth of 12 GHz. In the receiver, the de-chirp signal is sampled by an ADC with a sampling rate of 2.5 MSa/s. To investigate the performance of the established photonics-based radar, detection of two trihedral corner reflectors and turntable ISAR imaging are carried out.

![Configuration for detecting two trihedral corner reflectors](image)

**Fig. 2.** (a) Configuration for detecting two trihedral corner reflectors, (b) spectrum of the de-chirped signal when the two targets’ distance is 1.3 cm, and (c) the spectrum with the 27 cm distance.

Fig. 2(a) shows the picture of the two corner reflectors when they are separated by 1.3 cm along the radar line of sight. The de-chirped signal is sampled and analyzed by applying fast Fourier transform (FFT), with the result shown in Fig. 2(b). In Fig. 2(b), the two spectral speaks are located at 0.8747 MHz and 0.8803 MHz, respectively. The calculated distance between the two trihedral corner reflectors is 1.4 cm, which is very close to the real value. Fig. 2(c) shows the spectrum of the de-chirp signal when the two reflectors are separated by 27 cm. The two speaks are located at the 0.3613 MHz and 0.4694 MHz, respectively, and the calculated distance is 27.025 cm. The measurement error is 0.25 mm. The theoretical range resolution of the 12 GHz bandwidth radar is as high as 1.2 cm.
Then, turntable ISAR imaging of an airplane model is carried out. Fig. 3(a) shows the airplane model placed on a turntable, which rotates at a speed of 1 round per second. The airplane model’s fuselage is 29.2 cm and its wing length is 32 cm. The de-chirp signal is sampled at 2.5 MSa/s and the digital samples in a duration of 200 ms is recorded and used for ISAR imaging. The imaging result is shown in Fig. 3(b), where the profile of the airplane is clearly observed. Thus, a high-resolution imaging is achieved.

4. Conclusion

We have experimentally demonstrated a photonics-based Ka-band radar with a 12-GHz bandwidth. The system uses optical frequency quadrupling to generate broadband LFM signal and uses microwave photonic frequency mixing to realize de-chirp processing. A range resolution as high as 1.3 cm is achieved, and ISAR imaging of an airplane model is demonstrated. This experiment effectively verifies that microwave photonic radar has potentials to solve the future high-solution target imaging.

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5. References