Photonics-Based De-Chirping and Leakage Cancellation for Frequency-Modulated Continuous-Wave Radar System

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Abstract—A photonics-based leakage cancellation and echo signal de-chirping approach for frequency-modulated continuous-wave radar systems is proposed based on a dual-drive Mach–Zehnder modulator (DD-MZM). The de-chirp reference signal and the leakage cancellation reference signal are combined and applied to the upper arm of the DD-MZM, while the received signal, including the leakage signal and echo signals, is applied to the lower arm of the DD-MZM. When the amplitudes and delays of the leakage cancellation reference signal and the leakage signal are precisely matched, the leakage signal is canceled in the optical domain. The de-chirped signal is obtained after the leakage-free optical signal is detected in a photodetector. An experiment is performed. The cancellation depth of the leakage signal after de-chirping is around 23 dB when the frequency center and bandwidth of the linearly frequency-modulated signal are 11.5 and 2 GHz, respectively. When the leakage cancellation is not employed, the leakage will seriously affect the imaging results and distance measurement accuracy. When the leakage cancellation is enabled, the imaging results of multiple targets can be clearly distinguished, the distance measurement error of a moving target is significantly reduced to less than 10 cm, and a dynamic range increase of 21 dB is achieved.

Index Terms—De-chirping, electro-optical modulation, leakage cancellation, microwave photonics, RF microwave photonic devices.

I. INTRODUCTION

FREQUENCY-MODULATED continuous-wave (FMCW) radar systems have the advantages of simple structure, low average transmitting power, strong interference resistance, and no range blind zone [1] compared with pulse radar systems, because of their long signal duration and large bandwidth. Therefore, FMCW radars are widely used in various range and speed measurement applications [2], [3]. The main difference between FMCW radars and pulse radars is that FMCW radars transmit and receive signals at the same time. Therefore, the receiver in FMCW radars will receive a very strong leakage signal from the transmitter in addition to the radar echo signals. The leakage is mainly caused by insufficient circulator isolation when the transmitter and receiver share the same antenna [4] and caused by the free-space coupling between the transmitting antenna and receiving antenna when the transmitter and receiver use two independent antennas [5]. The leakage signal is also known as a self-interference signal, whose power is much greater than that of the echo signals reflected by the targets. Thus, the leakage signal is very easy to saturate the low-noise amplifier and analog-to-digital converter in the receiver, increase the noise floor of the de-chirped signal, and decrease the measurement dynamic range.

Since the leakage signal is much stronger, the cancellation of the leakage signal is often realized by combining multiple cancellation stages [6] from the receiving antenna to the receiver, including antenna domain cancellation, analog domain cancellation, and digital domain cancellation. In the antenna domain, the leakage can be suppressed by enlarging the distance between the transmitting and receiving antennas, minimizing their radiation beam overlap in space, using cross polarization, or adding absorber and reflective structures [6], when the transmitter and receiver each use an antenna. When the transmitter and receiver share a single antenna, the system has a more compact and lighter structure, but the leakage suppression is mainly limited by the isolation of the circulator. As important as the antenna domain cancellation, the analog domain cancellation is the key part to avoid receiver saturation. However, conventional electrical-based analog domain leakage cancellation methods are limited in working frequency/bandwidth and lack of tunability. With the advantages of large bandwidth, high frequency, good frequency tunability, and immunity to electromagnetic interference, microwave photonics [7] is a promising technique for processing microwave signals [8], which can be applied to wide bandwidth leakage cancellation.

In addition to the FMCW radar system, the in-band full-duplex (IBFD) communication system also suffers from the strong leakage signal due to simultaneous transmitting and receiving signals at the same frequency band [9]. The analog domain cancellation in both IBFD communication systems...
and FMCW radar systems is mainly based on constructing reference signals from the known transmitted signals to cancel the leakage signals. There are many similarities between IBFD communication systems and FMCW radar systems in the leakage cancellation studies. In the past few years, many studies [10, 11] have been carried out for different key problems in the photonics-based self-interference cancellation (SIC) system for the suppression of the self-interference signal in IBFD communication systems [12]–[27].

In [12]–[14], the self-interference was canceled by using two parallel Mach–Zehnder modulators (MZMs)/equivalent intensity modulators biased at opposite quadrature transmission points (QTPs). SIC was also achieved by using two modulators or modulated lasers and a balanced photodetector (PD) [15]–[18]. To avoid the instability of the SIC system with two optical paths, SIC methods based on a single modulator and a PD were proposed [19]–[26]. Furthermore, SIC methods combining frequency downconversion were widely studied [23]–[26]. Besides, SIC methods [26], [27] with high spectral efficiency of fiber transmission were also studied. In [28] and [29], different from the methods in [12]–[27], two SIC methods that did not need a reference signal were proposed. However, all these methods mentioned above are not specially designed for the FMCW radar system. Li et al. [30] studied the leakage cancellation for the FMCW radar system using a polarization-division-multiplexed MZM, and a 17.5-dB leakage cancellation depth at 15 GHz with a bandwidth of 2 GHz was achieved. Nevertheless, some unique characteristics of the FMCW radar are not reflected in [30], such as the de-chirping of the echo signals and the effect of leakage cancellation on the imaging and distance measurement. Thus, it is highly desirable that the cancellation performance of the leakage cancellation system is verified by taking the radar application, such as distance measurement and imaging, into consideration.

Furthermore, in FMCW radar systems, de-chirping is required for further radar signal processing, whereas the original spectrum of the echo signal does not need to be fully recovered. In fact, because the echo signals reflected from the targets commonly travel a much longer distance than the leakage signal between the two antennas, the frequency components corresponding to the echo signals and the leakage signal are separated in the de-chirped signal after the de-chirping process. Therefore, when the de-chirping function is incorporated into the leakage cancellation system, the cancellation in the analog domain is mainly to prevent the receiver from being saturated and decrease the noise floor of the de-chirped signal besides reducing the power of the de-chirped leakage signal, which is much different from the SIC in IBFD communication systems. In the IBFD communication systems, no de-chirping is needed and the original spectrum of the signal of interest has to be separated from that of the leakage signal directly. Therefore, it is worthwhile to study the radar leakage cancellation in conjunction with the de-chirping process.

In this article, a photonics-based leakage cancellation and echo signal de-chirping method for FMCW radar systems is proposed. The leakage is directly canceled in the optical domain in a dual-drive MZM (DD-MZM) and the echo signals are de-chirped after photodetection. To the best of our knowledge, this is the first photonics-based radar leakage cancellation and echo signal de-chirping system, and the effect of the leakage cancellation on radar imaging and distance measurement is studied for the first time. The power of the de-chirp reference signal is adjusted to decrease the de-chirped signal background noise to optimize the cancellation performance. After optimization, the cancellation depth of the leakage in the de-chirped signal is around 23 dB when the center frequency and bandwidth of the linearly frequency-modulated (LFM) signal are 11.5 and 2 GHz, respectively. When the leakage cancellation is disabled, the leakage signal seriously affects the imaging results and distance measurement accuracy of the radar system. When the leakage cancellation is enabled, the imaging results of multiple targets can be clearly distinguished, the distance measurement error of a moving target is significantly reduced to less than 10 cm, and a dynamic range increase of 21 dB is achieved.

II. PRINCIPLE

The schematic of the leakage cancellation and de-chirping method for the FMCW radar system is shown in Fig. 1. An optical signal generated from a continuous-wave (CW) laser diode (LD) is sent to a DD-MZM via a polarization controller (PC). The de-chirp reference signal and the leakage cancellation reference signal tapped from the radar transmitter are sent to the upper arm of the DD-MZM, whereas the received signal from the receiving antenna, including the leakage signal and the echo signal, is sent to the lower arm of the DD-MZM. The DD-MZM is biased at the minimum transmission point (MITP) [31] as shown in Fig. 1(a), where \( V_T \) represents the half-wave voltage of the DD-MZM. Since a \( \pi \) phase shift is introduced between the two arms, the leakage...
signal can be canceled in the optical domain. The leakage-free optical signal from the DD-MZM is injected into a PD, where the echo signals and the de-chirp reference signal beat with each other and the de-chirped signal for radar signal processing is generated. By using such a simple system, the leakage cancellation and radar echo signal de-chirping are simultaneously implemented.

It is assumed that the start angular frequency and chirp rate of the LFM signal are \( \omega_0 \) and \( f_E \), respectively. In this case, the de-chirp reference signal, the leakage cancellation reference signal, the leakage signal, and the echo signal can be expressed as

\[
V_D(t) = A_D \cos[\omega_0(t - \tau_D) + \pi k(t - \tau_D)^2] \\
V_R(t) = A_R \cos[\omega_0(t - \tau_R) + \pi k(t - \tau_R)^2] \\
V_L(t) = A_L \cos[\omega_0(t - \tau_L) + \pi k(t - \tau_L)^2] \\
V_E(t) = A_E \cos[\omega_0(t - \tau_E) + \pi k(t - \tau_E)^2]
\]

where \( A_D, A_R, A_L, \) and \( A_E \) are the amplitudes and \( \tau_D, \tau_R, \tau_L, \) and \( \tau_E \) are the delays of the corresponding signals. To simplify the following analysis, it is assumed that:

\[
\begin{align*}
\theta_D &= \omega_0(t - \tau_D) + \pi k(t - \tau_D)^2 \\
\theta_R &= \omega_0(t - \tau_R) + \pi k(t - \tau_R)^2 \\
\theta_L &= \omega_0(t - \tau_L) + \pi k(t - \tau_L)^2 \\
\theta_E &= \omega_0(t - \tau_E) + \pi k(t - \tau_E)^2.
\end{align*}
\]

Therefore, the four signals can be expressed as \( A_D \cos(\theta_D), A_R \cos(\theta_R), A_L \cos(\theta_L), \) and \( A_E \cos(\theta_E) \). The input optical signal from the LD is assumed to be \( \exp(j \omega_0 t) \), so the optical signal from the upper arm of the DD-MZM can be expressed as

\[
E_{upper}(t) = \frac{1}{\sqrt{2}} \exp[j \omega_0 t + j m_D \cos(\theta_D) + j m_R \cos(\theta_R)]
\]

\[
\approx \frac{1}{\sqrt{2}} \exp[j \omega_0 t] j_0(m_D) j_0(m_R) + 2 j j_1(m_D) j_0(m_R) \cos(\theta_D) + 2 j j_0(m_D) j_1(m_R) \cos(\theta_R) - 4 j_1(m_D) j_1(m_R) \cos(\theta_D) \cos(\theta_R)]
\]

where \( j_n(\cdot) \) is the \( n \)-th order Bessel function of the first kind and \( m_D = \pi A_D/V_E \) and \( m_R = \pi A_R/V_E \) are the modulation indices. In the derivation of (9), small-signal modulation condition \( (m_D, m_R < 1) \) is applied, so only the 1st-order optical sidebands are considered. The spectrum and time–frequency diagram of the optical signal from the upper arm of the DD-MZM are shown in Fig. 1(b). When the DD-MZM is biased at the MITP, the phase difference between two arms of the DD-MZM is \( \pi \). The optical signal from the lower arm of the DD-MZM is thus given by

\[
E_{lower}(t) = \frac{1}{\sqrt{2}} \exp[j \omega_0 t + j m_L \cos(\theta_L) + j m_E \cos(\theta_E) + j \pi]
\]

\[
\approx \frac{1}{\sqrt{2}} \exp[j \omega_0 t] j_0(m_L) j_0(m_E) + 2 j j_1(m_L) j_0(m_E) \cos(\theta_L) + 2 j j_0(m_L) j_1(m_E) \cos(\theta_E) - 4 j_1(m_L) j_1(m_E) \cos(\theta_L) \cos(\theta_E)]
\]

where \( m_L = \pi A_L/V_E \) and \( m_E = \pi A_E/V_E \) are the modulation indices. Small-signal modulation condition \( (m_L, m_E < 1) \) is also used in (10). The spectrum and time–frequency diagram of the optical signal from the lower arm of the DD-MZM are shown in Fig. 1(c). Considering the small-signal modulation conditions, we have \( j_0(\cdot) \approx 1 \) and \( j_1(\cdot) \ll j_0(\cdot) \), so the optical signal from the DD-MZM can be simplified as

\[
E_{DD-MZM}(t) \approx \exp[j \omega_0 t] (j j_1(m_D) \cos(\theta_D) + j j_1(m_R) \cos(\theta_R) - j j_1(m_L) \cos(\theta_L) - j j_1(m_E) \cos(\theta_E)).
\]

When \( \tau_L = \tau_R \) and \( A_R = A_L \) are established, the leakage signal is canceled by the leakage cancellation reference signal in the optical domain, and the optical signal from the DD-MZM can be expressed as

\[
E_{DD-MZM}(t) = \exp[j \omega_0 t] (j j_1(m_D) \cos(\theta_D) - j j_1(m_R) \cos(\theta_R)).
\]

As can be seen, besides the leakage signal, the optical carrier from the two arms of the DD-MZM is also canceled. The spectrum and time–frequency diagram corresponding to the optical signal from the DD-MZM are shown in Fig. 1(d). Then, the leakage-free optical signal from the DD-MZM is detected in the PD with a responsivity of \( R \). The photocurrent from the PD can be written as

\[
i_{PD}(t) = R |E_{DD-MZM}(t)|^2
\]

\[
= \frac{R}{2} [j j_1^2(m_D) + j j_1^2(m_R)] + j j_1^2(m_E) [1 + \cos(2\theta_E)]
- 2 j j_1(m_D) j_1(m_R) \cos(\theta_D + \theta_R) + \cos(\theta_D - \theta_R)].
\]

After low-pass filtering and assuming \( \tau_D = 0 \), the photocurrent from the PD can be expressed as

\[
i_{LPF}(t) = \frac{R}{2} [j j_1^2(m_D) + j j_1^2(m_E)] + j j_1^2(m_E) \cos(\omega_0 \tau_E + 2 \pi k t \tau_E - \pi k \tau_E^2)
- \pi j_1(m_D) j_1(m_E) \cos(\omega_0 \tau_E + 2 \pi k t \tau_E - \pi k \tau_E^2)]
\]

The de-chirped signal at the low-frequency band is obtained, whose frequency is

\[
f_E = k \tau_E.
\]

The spectrum corresponding to the de-chirped signal from the PD is shown in Fig. 1(e).

For the FMCW radar system, the distance measurement and the inverse synthetic aperture radar (ISAR) imaging can be implemented by further processing the de-chirped signal. According to (15), the distance can be derived as

\[
R = \frac{c}{2k} \tau_E
\]
where $c$ is the velocity of light in vacuum. To implement ISAR imaging, when the radar transmits a sequence of $N$ periods and each period of the de-chirped signal has $M$ samples, the 2-D image can be constructed by the rearranged $M \times N$ matrix from the $N \times M$ samples [32], [33]. The ISAR imaging range and the cross-range resolution are expressed as

$$R_R = \frac{c}{2B}$$

$$R_c = \frac{\lambda}{2T_i\Omega}$$

where $B$, $\lambda$, $T_i$, and $\Omega$ are the LFM signal bandwidth, the LFM signal center wavelength, the integration time, and the rotating speed of the imaging targets, respectively.

### III. EXPERIMENT AND RESULTS

#### A. Experimental Setup

An experiment is carried out based on the setup shown in Fig. 2. A 15.5-dBm CW light wave generated from an LD (ID Photonics CoBriteDX1-1-C-H01-FA) with a wavelength of 1548.9 nm is injected into a DD-MZM (Fujitsu FTM7937EZ200) via a PC. All the LFM signals, including the transmitted signal, the leakage signal, the leakage cancellation reference signal, and the de-chirp reference signal, are generated from an arbitrary waveform generator (AWG, Keysight M8190A), whereas the local oscillator (LO) signal is generated from a microwave signal generator (MSG, Agilent 83630B).

An intermediate frequency (IF) LFM signal from the AWG is first upconverted to the higher frequency band using a 7-dBm LO signal via an electrical mixer (M/A-COM M14A), and then, the upconverted LFM signal is filtered by an electrical bandpass filter (BPF, KGL YA356-2, 10.4–14.1 GHz). The signal from the BPF is divided into two parts by an electrical coupler (EC1, MCLI PS2-11, 2–18 GHz, −3 dB). One output from EC1 is sent to EC2 (Narda 4456-2, 2–18 GHz, −3 dB) through a tunable electrical attenuator (ATT1, Norsal IND 7131-10, 10–20 GHz) and an electrical amplifier (EA1, CLM 145-7039-293B, 5.85–14.50 GHz, 39 dB) as the de-chirp reference signal. The other output from EC1 is split into two parts by a directional coupler (EC3, KRYTAR, MODEL 1818, 2–18 GHz, −16 dB) via EA2 (CLM 145-7039-293B, 5.85–14.50 GHz, 39 dB). The coupled output of EC3 is split into two parts again by EC4 (AEROFLEX YL-56, 7–14 GHz, −3 dB). One output from EC4 is sent to EC2 through ATT2 (Narda 4799, 4–18 GHz) and a tunable electrical delay line (DL, Sage 6705) as the leakage cancellation reference signal. The de-chirp reference signal and the leakage cancellation reference signal are combined at EC2 and then applied to the upper arm of the DD-MZM.

The direct output of EC3 is fed into a transmitting antenna (GHA080180-SMF-14, 8–18 GHz) and then radiated for target detection. Due to the limited radiation power and short target distance in the experiment, the leakage signal from the transmitting antenna to the receiving antenna has even much less power than the echo signal from the target. Therefore, another output of EC4 is used to simulate a strong leakage signal whose power is much greater than that of the echo signals and is injected into EC5 (Narda 4456-2, 2–18 GHz, −3 dB). The signals from a receiving antenna (GHA080180-SMF-14, 8–18 GHz) are used to simulate the echo signals. The echo signals through ATT3 (Norsal IND 7131-10, 10–20 GHz) and EA3 (ALM 145-5023-293 5.85–14.5 GHz, 23 dB) are combined with the strong leakage signal at EC5 to simulate the received signal corresponding to the real-world application, which is then applied to the lower arm of the DD-MZM.

It should be noted that ATT1 and EA1 are used to adjust the power of the de-chirp reference signal for system performance optimization; ATT3 and EA3 are used to adjust the power of the echo signals to study the system performance; ATT2 and the DL are used to match the amplitudes and delays of the leakage cancellation reference signal and leakage signal for leakage cancellation. When the amplitudes and delays of the leakage cancellation reference signal and leakage signal are precisely matched and the DD-MZM is biased at the MITP, the leakage signal can be canceled in the optical domain. Then, the optical signal from the DD-MZM is injected into a PD (Nortel Networks PP-10G). The waveforms of the de-chirped signal from the PD are captured by an oscilloscope (OSC, R&S RTO2032) with a digital low-pass filter.

#### B. Cancellation Performance Without Echo Signals

First, the leakage cancellation performance without echo signals is investigated in both optical and electrical domains. It should be pointed out here that for the convenience of description and experiment, all subsequent echo signal power in this article refers to the power of the echo signal input to EC5 after the echo signal is received by the receiving antenna, attenuated by ATT3, and amplified by EA3.

To investigate the leakage cancellation performance in the optical domain, the peak-to-peak amplitude of the IF LFM signal from the AWG is set to 500 mV, the period of the IF LFM signal is set to 0.1 ms, the center frequency of the IF LFM signal is set to 2 GHz, the bandwidth of the IF LFM signal is set to 1 or 2 GHz, and the frequency of the LO signal from the MSG is set to 9.5 GHz. In this case, the center frequency of the LFM signal from the BPF is 11.5 GHz, while the bandwidth of the LFM signal from the

![Fig. 2. Experimental setup of the proposed leakage cancellation and de-chirping system. AWG: arbitrary waveform generator; MSG: microwave signal generator; LFM: linearly frequency-modulated signal; LO: local oscillator; BPF: bandpass filter; EC: electrical coupler; EA: electrical amplifier; ATT: attenuator; DL: delay line; LD: laser diode; PC: polarization controller; DD-MZM: dual-drive Mach–Zehnder modulator; PD: photodetector; OSC: oscilloscope.](image-url)
The power of the leakage signal is around −3 dBm. The optical signal from the DD-MZM is observed using an optical spectrum analyzer (OSA, ANDO AQ6317B). Fig. 3(a) shows the optical spectra of the optical signal from the DD-MZM with and without leakage cancellation when the de-chirp reference signal and the echo signals are not applied to the DD-MZM. The blue solid line shows the optical spectrum without leakage cancellation by disconnecting the leakage cancellation reference signal from the system, whereas the red dashed line shows the optical spectrum with leakage cancellation when the bandwidth of the LFM signal is 2 GHz. It can be seen that the cancellation depth of the leakage sideband is around 23.1 dB. It should be noted that the optical carrier is suppressed since the DD-MZM is biased at the MITP. In Fig. 3, the carrier and the sidebands have close power because the power of the leakage signal is as low as −3 dBm. When the bandwidth of the LFM signal is decreased to 1 GHz, the cancellation depth of the leakage sideband changes to 24.5 dB, as shown in Fig. 3(b). The blue solid line in Fig. 3(c) shows the optical spectrum when only the de-chirp reference signal with a power of −5.3 dBm is applied to the DD-MZM. The red dashed line, yellow dotted line, and purple dashed-dotted line in Fig. 3(c) show the optical spectra when only echo signals with the power of −10.6, −15.1, and −20.3 dBm are applied to the DD-MZM.

The de-chirped signal can be obtained after photodetection when the de-chirp reference signal is applied. When the de-chirp reference signal is enabled, the leakage cancellation performance with different de-chirp reference signal power is investigated. In this study, the echo signals are also not applied. The de-chirp reference signal power is adjusted by tuning ATT1. The center frequency and bandwidth of the LFM signal from the BPF are 11.5 and 2 GHz, respectively. The power of the leakage signal is around −3 dBm. The waveforms of the de-chirped signal from the PD are captured by the OSC with a 4-MSa/s sampling rate, and the electrical spectra of the de-chirped signal are obtained from the waveforms using the fast Fourier transform.

The electrical spectra of the de-chirped signal with and without leakage cancellation are shown in Fig. 4. Because the length of the waveform used for fast Fourier transform is 20 ms, which is 200 times the LFM signal period, discrete spectra are obtained in Fig. 4. Fig. 4(a) shows that the leakage cancellation depth and de-chirped signal background noise cancellation depth are 24.2 and 3.6 dB, respectively, when the power of the de-chirp reference signal is −0.8 dBm. When the power of the de-chirp reference signal is further increased to −9.6 dBm, the de-chirped signal background noise cancellation depth is increased to 10 dB, while the leakage cancellation depth still has no significant change, as shown in Fig. 4(c). It is indicated from Fig. 4 that the power of the de-chirp reference signal almost does not affect the depth of leakage cancellation. Smaller de-chirp reference signal power introduces less de-chirped signal background noise and also smaller power of the de-chirped signal. Therefore, the de-chirp reference signal power should be properly set. According to these results, the system performance optimization can be achieved by adjusting the de-chirp reference signal power. If the power of the de-chirp reference signal is not properly set, the leakage cancellation with a larger leakage cancellation depth does not guarantee an improved radar imaging and measurement performance because of the de-chirped signal background noise.

In Fig. 4, the frequency component in the de-chirped signal corresponding to the leakage signal is at around 120 kHz, which corresponds to a distance of 1.8 m. These two values are indeed determined by the cable lengths used in the experiment.

C. Leakage Cancellation and ISAR Imaging

Then, the imaging targets are employed in the experiment. The leakage cancellation performance with echo signals reflected by the imaging targets and the effect of leakage cancellation on ISAR imaging are further studied. One cuboid and two cylinders are used as the targets, which are placed on the turntable, as shown in Fig. 5(a). The distance between the center of the turntable and the antenna pair is around 1.89 m.

The electrical spectra and power are measured using an electrical spectrum analyzer (ESA, R&S FSP-40). When measuring the electrical spectra and power of the LFM signals, the turntable is not rotated. The center frequency and bandwidth of the LFM signal from the BPF are 11.5 and 2 GHz, respectively.
The power of the leakage signal is $-3$ dBm. The power of the de-chirp reference signal is set to $-9.6$ dBm. The power of the LFM signal fed into the transmitting antenna is around 20 dBm and the in-band signal-to-noise ratio (SNR) is around 64 dB.

The electrical spectra of the echo signals with different powers of $-10.6$, $-15.1$, and $-20.3$ dBm are shown in Fig. 5(b), and the corresponding in-band SNRs are measured to be 37.3, 33.0, and 27.8 dB. Many ripples are observed in the spectra, which are mainly caused by the superposition of echo signals from different reflection paths. The ripples are similar in shape for different echo signal power because the position of the reflecting objects does not change when the power is adjusted.

Fig. 5(c) shows the electrical spectra of the echo signals when the targets are removed from the turntable. More ripples are observed when the imaging targets are removed, which are caused by the reflection of the LFM signals in the background environment. The blue line in Fig. 5(d) shows the electrical spectrum of a $-3$-dBm leakage signal, whereas the red line shows that of a $-9.6$-dBm de-chirp reference signal.

To investigate the leakage cancellation performance and the effect of leakage cancellation on ISAR imaging, the imaging targets rotate clockwise with the turntable for a period of 24.56 s. The de-chirped signal is captured by the OSC with a 4-MSa/s sampling rate, and the sampling time of the de-chirped signal is 2000 ms. Fig. 6(a) shows the schematic of the target imaging. Within 2000 ms, the turntable rotates around 29.3°. The center frequency and bandwidth of the LFM signal from the BPF are 11.5 and 2 GHz, respectively. The period of the LFM signal is set to 0.1 ms. The power of the leakage signal is $-3$ dBm. The power of the de-chirp reference signal is set to $-9.6$ dBm. Fig. 6(b) shows the temporal waveforms of the de-chirped signal with and without leakage cancellation when the echo signal power is $-20.3$ dBm. After leakage cancellation, because the dominant de-chirped leakage signal is effectively eliminated, the waveform amplitude is significantly reduced and the de-chirped echo signal with less power is left. Furthermore, the waveform amplitude changes with time and the waveform amplitude reaches the maximum at about 1000 ms after leakage cancellation because the cuboid is right in front of the antenna at that moment and more echo signals can be reflected. Fig. 6(c) shows a section of the temporal waveform from 0 to 0.2 ms in two periods. The waveforms are very similar at two adjacent periods due to the very small rotation angle of the turntable within 0.2 ms.

Fig. 7(a) shows the schematic of the photonic de-chirping process when the leakage cancellation is not employed. Fig. 7(a-i) shows the time–frequency diagram of the +1st-order optical sidebands of the optical signal from the DD-MZM when the cuboid is farthest away from the antenna pair and the two cylinders are closest to the antenna pair.
The corresponding diagram of the –1st-order sidebands is similar and not shown here. Fig. 7(a–ii) shows the electrical spectra of the de-chirped signal. It can be seen that besides the de-chirped leakage signal and the de-chirped echo signals, the de-chirped interferences are introduced due to the beating between the 1st-order optical sideband of the leakage and the 1st-order optical sideband of the echo signals. Thus, the de-chirped signals mainly include the de-chirped leakage signal, the de-chirped echo signals, and the de-chirped interferences.

Then, the leakage cancellation performance with different echo signal power is studied in the electrical domain. The center frequency and bandwidth of the LFM signal from the BPF are 11.5 and 2 GHz, respectively. The power of the leakage signal is $-3$ dBm. The power of the de-chirp reference signal is set to $-9.6$ dBm. Fig. 7(b) shows the corresponding electrical spectrum of Fig. 6(b) when the echo signal power is $-20.3$ dBm. The blue dotted line shows the electrical spectrum without leakage cancellation, and the frequency of the de-chirped leakage signal is around 120 kHz. The frequency range of the de-chirped echo signal corresponding to the cuboid and the two cylinders is about from 290 to 300 kHz and about from 210 to 230 kHz, respectively. Since the distances between the antenna pair and the three imaging targets change with the rotation of the turntable, the frequency of the de-chirped echo signals changes in a frequency range. Furthermore, the frequency ranges of the de-chirped interferences are around from 90 to 110 kHz and from 170 to 180 kHz. It can be seen that the de-chirped interferences also influence the acquisition of the echo signal information when the leakage signal is not canceled. In the experiment, the cable lengths are carefully selected to make these three mentioned signals not overlap with each other. In real-world FMCW radar systems, the three signals are naturally separated because the echo signal always travels a much longer distance than the leakage signal.

The purple solid line in Fig. 7(b) shows the electrical spectrum of the de-chirped signal background noise when the leakage signal is not applied to the DD-MZM and the imaging targets are removed. The red dashed line in Fig. 7(b) shows the electrical spectrum with leakage cancellation. As can be seen, the leakage cancellation depth is around 22.8 dB, and the de-chirped interference is also much suppressed. The de-chirped interferences are decreased because the leakage is canceled in the optical domain, and the de-chirped interference is obtained by beating the 1st-order optical sidebands of the leakage and the echo signals. It is also observed from Fig. 7(b) that the de-chirped signal of the targets is around 9.6 dB higher than the de-chirped signal background noise. When the echo signal power is increased to $-15.1$ dBm, the cancellation depth is increased slightly to 23.1 dB and the de-chirped signal of the targets is 14.3 dB higher than the de-chirped signal background noise, as shown in Fig. 7(c). When the echo signal power is further increased to $-10.6$ dBm, the cancellation depth increases to 23.8 dB and the de-chirped signal of the targets is 16.9 dB higher than the de-chirped signal background noise, as shown in Fig. 7(d). It can be summarized that the de-chirped leakage signal and the de-chirped interferences can be effectively suppressed after leakage cancellation.

Afterward, the leakage cancellation performance is evaluated by implementing ISAR imaging. The waveforms of the de-chirped signal captured by the OSC are postprocessed using MATLAB, and a digital high-pass filter with a 140-kHz 3-dB cutoff frequency is also used to further suppress the residual de-chirped leakage signal and de-chirped interferences. In this study, the center frequency and bandwidth of the LFM signal from the BPF are 11.5 and 2 GHz, respectively. The power of the leakage signal is $-3$ dBm. The power of the de-chirp reference signal is set to $-9.6$ dBm. According to (17) and (18), the theoretical range and cross-range resolutions are 7.5 and 2.55 cm, respectively.

Fig. 8(a) shows the schematic of the positions of the three imaging targets. Fig. 8(b)–(h) shows the imaging results under different conditions. Note that all imaging data are normalized, and the maximum value for normalization is selected from all the data corresponding to Fig. 8(b)–(h). Fig. 8(b) shows the imaging result when the leakage signal is not applied and the imaging targets are removed, which is used to show the influence of the background environment.
on the imaging results. The imaging results of the three targets without and with leakage cancellation are shown in Fig. 8(c) and (d) when the echo signal power is $-20.3$ dBm. It can be seen that the imaging results are very blurred when the leakage cancellation is not enabled because the leakage and the de-chirped interference are too strong. It should be noted that the strength of the interference also depends on the leakage. When the leakage is canceled in the optical domain, the influence of the de-chirped interference signal on imaging is also greatly weakened. The interference shown in Fig. 8(c) corresponds to the cuboid and the interferences corresponding to the two cylinders are not shown in Fig. 8(c) because it is much suppressed by the digital high-pass filter. After leakage cancellation, one cuboid and two cylinders are clearly distinguished in Fig. 8(d). When the power of the echo signal is increased to $-15.1$ dBm, the difference between the echo signal power and the leakage signal power is reduced. The corresponding imaging results without and with leakage cancellation are shown in Fig. 8(e) and (f). When the power of the echo signal is further increased to $-10.6$ dBm, the corresponding results are shown in Fig. 8(g) and (h). Note that the influence of the background environment on the imaging results shown in Fig. 8(b) can also be observed in Fig.8 (c)–(h) due to the background environment. It can also be seen from Fig. 8 that, when the echo signal power is relatively small, the imaging results after leakage cancellation are still influenced by the residual leakage, the residual interference, and the background noise. When the echo signal power is increased, the influence of the residual leakage, the residual interference, and the background noise are decreased and clearer imaging results can be obtained after leakage cancellation.

**D. Leakage Cancellation and Distance Measurement**

Finally, a single target is placed on the turntable to verify the leakage cancellation performance through the target distance measurement. In this study, the center frequency and bandwidth of the LFM signal from the BPF are 11.5 and 2 GHz, respectively, the power of the leakage signal is $-3$ dBm, and the power of the de-chirped reference signal is changed to $-12.8$ dBm by tuning ATT1. One cylinder is used as the target. The radius and height of the target are 5 and 15 cm, respectively. The target is placed on the turntable, as shown in Fig. 9(a). The distance $L_2$ between the cylinder and the center of the turntable is 45 cm, and the distance $L_1$ between the antenna pair and the center of the turntable is 155 cm. In the experiment, the turntable rotates clockwise with a period of 24.56 s. During the rotation, the echo signal is sampled every 1/32 period with a 10-ms sampling time for a total of 33 samples. In addition, five measurements are implemented with and without leakage cancellation. Since the distance between the antenna pair and the target varies from 110 to 200 cm, the distance measurement range is set from 109 to 225 cm and the corresponding de-chirped frequency range is from 145 to 300 kHz. It should be noted that the frequency of the de-chirped leakage signal is around 120 kHz.

The distance measurement results with leakage cancellation are shown in Fig. 9(b) and (c). Fig. 9(b) shows five distance measurement results. In Fig. 9(c), the mean distance values of the five measurements, the theoretical distance values, and the standard deviations of the distance measurement errors are represented by blue diamonds, blue circles, and red error bars, respectively. Fig. 9(d) shows the results of one distance measurement without leakage cancellation. The measured distance values, the theoretical distance values, and the measurement errors are represented by blue diamonds, blue circles, and red squares, respectively. It can be seen that the distance measurement can be achieved after leakage cancellation. In Fig. 9(c), the standard deviation of the fifth and seventh sampling is larger because one or two corresponding measurements are incorrect due to the low echo signal power, as shown in Fig. 9(b). Excluding the three data that are measured incorrectly, the measurement error of the moving target is less than 10 cm after leakage cancellation. As shown in Fig. 9(d), when the leakage cancellation is disabled, most of the measurements are wrong. It can be explained according to the results in Fig. 9(e) and (f), which shows the electrical spectra of the de-chirped signal with and without leakage cancellation in the seventh and 24th samples. It can be seen that when the leakage is not canceled, the power at 150 or 160 kHz is always the maximum in the frequency search range from 145 to 300 kHz. When the leakage is canceled, the noise is decreased and the frequency of the de-chirped echo signal can be correctly found, as shown by the red solid line in Fig. 9(e) and (f).
IV. DISCUSSION

A. Impact of Power and Time Delay Mismatch

To analyze the penalty for power and delay mismatch on the leakage cancellation depth after de-chirping, a simulation is carried out. In the simulation, the DD-MZM has an extinction ratio of 30 dB and a half-wave voltage of 3.5 V, the center frequency and bandwidth of the LFM signal are 11.5 and 2 GHz, respectively, the power of the leakage signal is set to −3 dBm, the power of the de-chirp reference signal is set to −9.6 dBm, and the echo signal is not applied. Fig. 10(a) shows the impact of power mismatch and time delay mismatch on the cancellation depth when the period of the LFM signal is set to 838.85 ns. As can be seen, the cancellation depth is larger than 20 dB when the power mismatch is lower than 0.8 dB and the time delay mismatch is lower than 1 ps. Due to the limited simulation environment, the period of the LFM signal in the simulation is different from that in the former experiment. Furthermore, the cancellation depths at different LFM periods with different mismatch parameters are shown in Fig. 10(b). It can be seen that the cancellation depth is virtually unaffected by the LFM periods when the period is changed from 16.777 to 1677.7 ns.

B. Dynamic Range and Sensitivity

The system dynamic range is further investigated by experiments. In this study, the transmitting antenna, receiving antenna, and EA3 are removed and replaced by RF cables. The direct output of EC3 is fed into ATT3 directly and ATT3 and some additional fixed electrical attenuators are used to adjust the power of the echo signal. The power of the leakage signal is set to −3 dBm and that of the de-chirp reference signal is set to −9.6 dBm. Fig. 11(a) and (b) shows the electrical spectra of the de-chirped signal at different echo power without and with leakage cancellation in a single period. It is observed that there is a 21-dB dynamic range improvement when the leakage cancellation is enabled. Fig. 11(c) shows the SNR and signal-to-interference ratio (SIR) of the de-chirped signal. It should be noted that the noise bandwidth is set to 10 kHz in calculating the SNR and the interference in the SIR includes de-chirped leakage and de-chirped interference. When the leakage cancellation is enabled, the power of the de-chirped interference and the de-chirped leakage is very close to the noise floor. When the leakage cancellation is disabled, the de-chirped interference power is changed with the echo power, and the de-chirped leakage power is stabilized at around −39 dBm. As can be seen, when the leakage cancellation is not implemented, not only the noise floor of the de-chirped signal is high and the dynamic range is small, but also the de-chirped interference still influences the system performance when the echo power is large.

Indeed, the system dynamic range, as well as the system sensitivity, is highly related to the noise figure (NF) and system bandwidth [34], [35]. When the bandwidth is fixed, reducing the system NF is an effective way to improve the dynamic range and sensitivity. Typically, the NF of a microwave photonic system often exceeds 15 dB, even more than 20 dB, which is at a disadvantage compared with its electrical competitors. However, the NF can be improved by using laser sources with high power and low relative intensity noise, low loss optical devices, modulators with low half-wave voltage, and high-responsivity PDs. The system NF can be reduced to less than 5 dB by using these methods in conjunction with some specific designs [35], which is very close to the NF of the electrical-based receiver.

C. Considerations in Practical Applications

Since the de-chirping operation is implemented simultaneously with the leakage cancellation, the de-chirped signal from the PD has a very low frequency, which is less than 1 MHz in this work. Therefore, the bandwidth of the PD is not a limitation of the proposed method. Different from the PD, the DD-MZM used in the system needs to have an operating bandwidth no less than the frequency of the received signal and leakage signal. The bandwidth of commercially available modulators is up to 110 GHz, so we also believe that the bandwidth of the DD-MZM is also not a limitation, and the proposed system can meet the needs of most applications by using a DD-MZM with larger operating bandwidth.

Compared with mature integrated circuit solutions, the proposed system is demonstrated based on discrete optoelectronic devices, which may be a little expensive and bulky. However, the size of the proposed system can be greatly reduced by integrated microwave photonics [10], [36], and the cost can also be reduced as the photonic integrated technique continues to mature.
Returning to the system function, in addition to the FMCW radar system, the proposed system can also be applied to reduce the leakage signals in other kinds of radar systems, such as stepped-frequency CW radars. It can also be used to suppress the self-interference signal in IBFD communication systems. In these cases, a frequency downconversion process followed by IQ demodulation in the IF band is used instead of further signal processing instead of the de-chirping process in FMCW radars. Therefore, the de-chirp reference shown in Fig. 1 should be replaced by a corresponding LO signal.

V. CONCLUSION

In summary, we have demonstrated a leakage cancellation and echo signal de-chirping approach for FMCW radar systems. The key significance of the work was that, for the first time, it combined the leakage cancellation and echo signal de-chirping in a single DD-MZM and the effect of leakage cancellation on the imaging and distance measurement of FMCW radar systems was studied. The cancellation performance with different de-chirp reference powers and different echo signal powers was verified, and the power of the de-chirp reference signal was adjusted to optimize the cancellation performance. The cancellation depth of the leakage signal after de-chirping was around 23 dB when the LFM center frequency and bandwidth were 11.5 and 2 GHz, respectively. After the leakage cancellation, the imaging results of multiple imaging targets were clearly distinguished, the distance measurement error of a moving target was significantly reduced to less than 10 cm, and a dynamic range increase of 21 dB was achieved.

REFERENCES

[1] A. G. Stove, “Linear FMCW radar techniques,” IEEE Proc. F Radar Signal Process., vol. 139, no. 5, pp. 343–350, Oct. 1992.
[2] A. Melzer, A. Onic, F. Starzer, and M. Huemer, “Short-range leakage cancellation in FMCW radar transceivers using an artificial on-chip target,” IEEE J. Sel. Topics Signal Process., vol. 9, no. 8, pp. 1650–1660, Dec. 2015.
[3] A. Cho, Y. S. Kang, B. J. Park, C. S. You, and S. O. Koo, “Altitude integration of radar altimeter and GPS/INS for automatic takeoff and landing of a UAV,” in Proc. Int. Conf. Control, Autom. Syst., Gyeonggi-do, South Korea, Oct. 2011, pp. 1429–1432.
[4] K. Lin, Y. E. Wang, C.-K. Pao, and Y.-C. Shih, “A Ka-band FMCW radar front-end with adaptive leakage cancellation,” IEEE Trans. Microw. Theory Tech., vol. 54, no. 12, pp. 4041–4048, Dec. 2006.
[5] Z. Li and K. Wu, “On the leakage of FMCW radar front-end receiver,” in Proc. Global Symp. Millim. Waves, Apr. 2008, pp. 127–130.
[6] K. E. Kolodziej, B. T. Perry, and J. S. Herd, “In-band full-duplex technology: Techniques and systems survey,” IEEE Trans. Microw. Theory Tech., vol. 67, no. 7, pp. 3025–3041, Jul. 2019.
[7] J. Yao, “Microwave photonics,” J. Lightw. Technol., vol. 27, no. 3, pp. 314–335, Feb. 1, 2009.
[8] J. Capmany, J. Mora, I. Gasulla, J. Sancho, J. Llorot, and S. Sales, “Microwave photonic signal processing,” J. Lightw. Technol., vol. 31, no. 4, pp. 571–586, Feb. 2013.
[9] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, “In-band full-duplex wireless: Challenges and opportunities,” IEEE J. Sel. Areas Commun., vol. 32, no. 9, pp. 1637–1652, Sep. 2014.
[10] X. Han et al., “RF self-interference cancellation by using photonic technology [invited],” Chin. Opt. Lett., vol. 19, no. 7, Jul. 2021, Art. no. 073901.
[11] V. J. Urick, M. E. Godinez, and D. C. Mikeska, “Photonic assisted radio-frequency interference mitigation,” J. Lightw. Technol., vol. 38, no. 6, pp. 1268–1274, Mar. 15, 2020.
[12] J. Suarez, K. Kravtsov, and P. R. Prucnal, “Incoherent method of optical interference cancellation for radio-frequency communications,” IEEE J. Quantum Electron., vol. 45, no. 4, pp. 402–408, Apr. 2009.
[13] J. Chang and P. R. Prucnal, “A novel analog photonic method for broadband multipath interference cancellation,” IEEE Microw. Wireless Compon. Lett., vol. 23, no. 7, pp. 377–379, Jul. 2013.
[14] W. Zhou, P. Xiang, Z. Niu, M. Wang, and S. Pan, “Wideband optical multichannel interference cancellation based on a dispersive element,” IEEE Photon. Technol. Lett., vol. 28, no. 8, pp. 849–851, Apr. 2016.
[15] M. P. Chang, M. Fok, A. Hofmaier, and P. R. Prucnal, “Optical analog self-interference cancellation using electro-absorption modulators,” IEEE Microw. Wireless Compon. Lett., vol. 23, no. 2, pp. 99–101, Feb. 2013.
[16] L. Zheng, Y. Zhang, S. Xiao, L. Huang, J. Fang, and W. Hu, “Adaptive optical self-interference cancellation for in-band full-duplex systems using regular triangle algorithm,” Opt. Express, vol. 27, no. 4, pp. 4116–4125, Feb. 2019.
[17] Z. Zhang, L. Zheng, S. Xiao, Z. Liu, J. Fang, and W. Hu, “Real-time IBFD transmission system based on adaptive optical self-interference cancellation using the hybrid criteria regular triangle algorithm,” Opt. Lett., vol. 46, no. 5, pp. 1069–1072, Mar. 2021.
[18] Y. Zhang, L. Li, S. Xiao, M. Bi, Y. Yu, and W. Hu, “Wideband over-the-air RF self-interference cancellation by an EML-based optical system with baseband predistortion,” IEEE Photon. J., vol. 9, no. 5, Oct. 2017, Art. no. 5503009.
[19] X. Han, B. Huo, Y. Shao, and M. Zhao, “Optical RF self-interference cancellation by using an integrated dual-parallel MZM,” IEEE Photon. J., vol. 9, no. 2, Apr. 2017, Art. no. 5501308.
[20] X. Li et al., “Optimized self-interference cancellation based on optical dual-parallel MZM for co-frequency and co-time full duplex wireless communication under nonlinear distortion and emulated multipath effect,” Opt. Express, vol. 27, no. 26, pp. 37286–37297, Dec. 2019.
[21] Y. Zhang, S. Xiao, H. Feng, L. Zhang, Z. Zhou, and W. Hu, “Self-interference cancellation using dual-drive Mach-Zehnder modulator for in-band full-duplex radio-over-fiber system,” Opt. Express, vol. 23, no. 26, pp. 32205–32213, Dec. 2015.
[22] L. Zheng, Z. Liu, S. Xiao, M. P. Fok, Z. Zhang, and W. Hu, “Hybrid wideband multipath self-interference cancellation with an LMS pre-adaptive filter for in-band full-duplex OFDM signal transmission,” Opt. Lett., vol. 45, no. 23, pp. 6382–6385, Dec. 2020.
[23] Y. Chen and S. Pan, “Simultaneous wideband radio-frequency self-interference cancellation and frequency downconversion for in-band full-duplex radio-over-fiber systems,” Opt. Lett., vol. 43, no. 13, pp. 3124–3127, Jul. 2018.
[24] B. Wang, Y. Chen, and Y. Chen, “Photonic-assisted wideband frequency downconverter with self-interference cancellation and image rejection,” Appl. Opt., vol. 58, no. 13, pp. 3539–3547, May 2019.
[25] S. Zhu, M. Li, N. H. Zhu, and W. Li, “Photonic radio frequency self-interference cancellation and harmonic down-conversion for in-band full-duplex radio-over-fiber system,” IEEE Photon. J., vol. 11, no. 5, Oct. 2019, Art. no. 5503110.
[26] Y. Chen and J. Yao, “Photonic-assisted RF self-interference cancellation with improved spectrum efficiency and fiber transmission capability,” J. Lightw. Technol., vol. 38, no. 4, pp. 761–768, Feb. 2020.
[27] T. Shi, M. Han, and Y. Chen, “Photonic-based analog and digital RF self-interference cancellation with high spectral efficiency,” Appl. Opt., vol. 60, no. 33, pp. 10299–10304, Nov. 2021.
[28] V. J. Urick, J. F. Diehl, C. E. Sunderman, J. D. McKinney, and K. J. Williams, “An optical technique for radio frequency interference mitigation,” IEEE Photon. Technol. Lett., vol. 27, no. 12, pp. 1333–1336, Jun. 2015.
[29] C. H. Cox and E. I. Ackerman, “TIPRs: A transmit-isolating photonic receiver,” J. Lightw. Technol., vol. 32, no. 20, pp. 3630–3636, Oct. 2014.
[30] P. Li et al., “Photonic-assisted leakage cancellation for wideband frequency modulation continuous-wave radar transceiver,” J. Lightw. Technol., vol. 38, no. 6, pp. 1178–1183, Mar. 2020.
[31] V. J. Urick, J. D. McKinney, and K. J. Williams, Fundamentals of Microwave Photonics. Hoboken, NJ, USA: Wiley, 2015.
[32] V. C. Chen and M. Martorella, Inverse Synthetic Aperture Radar Imaging: Principles, Algorithms and Applications. Herts, U.K.: SciTech, 2014.
[33] D. Liang, L. Jiang, and Y. Chen, “Multi-functional microwave photonic radar system for simultaneous distance and velocity measurement and high-resolution microwave imaging,” J. Lightw. Technol., vol. 39, no. 20, pp. 6470–6478, Oct. 2021.
[34] R. W. Ridgway, C. L. Dohrman, and J. A. Conway, “Microwave photonics programs at DARPA,” J. Lightw. Technol., vol. 32, no. 20, pp. 3428–3439, Oct. 2014.

[35] C. Cox, Analog Optical Links: Theory and Practice. Cambridge, U.K.: Cambridge Univ. Press, 2006.

[36] D. Marpaung, J. Yao, and J. Capmany, “Integrated microwave photonics,” Nature Photon., vol. 13, no. 2, pp. 80–90, Feb. 2019.

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