Microwave Photonic System for Nonuniform Frequency Diverse Array Radar

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***Abstract*—A microwave photonic system, which has the ability of providing amplitude, frequency and phase control of a microwave signal, for use in a nonuniform frequency diverse array (FDA) radar is proposed and experimentally demonstrated. Microwave signal amplitude and phase controls are realized by adjusting the bias voltages of a dual-polarization dual-parallel Mach Zehnder modulator. A frequency offset on the microwave signal, which is needed in an FDA radar, is introduced by Serrodyne modulation. A range, angle and time dependent beampattern can be generated by controlling the amplitude, frequency and phase of a microwave signal in each array element of an FDA radar. Experimental results are presented that demonstrate the proposed structure can generate the frequency offsets required for a 32-element nonuniform FDA radar. Using the measured frequency offsets, a dot-shaped beampattern can be produced by a nonuniform FDA radar.**

Keywords—Frequency diverse array, frequency shifting, dot-shaped beampattern, microwave photonics.

I. Introduction

The traditional mechanical scanning radar changes the radar beam direction by mechanically rotating the radar antenna, which suffers from a low radar scanning speed. Subsequently, the concept of phased array radar is proposed [1], which overcomes the speed limitation of mechanical scanning. A phased array radar changes the direction of the radar beam by shifting the phase of the signal transmitted by the array radar. Besides a fast scanning speed, an array radar has higher radiation power and larger equivalent aperture, which results in a wider detection distance and a higher angular resolution, compared to the traditional radar that uses a single antenna. However, the beampattern of a conventional phased array radar, which is designed by controlling the amplitude and phase of the signal transmitted by each array element of the radar, does not contain the range information. Therefore, the radar cannot detect and estimate range-dependent targets due to an inherent range ambiguity [2].

A new concept of array radar, named frequency diverse array (FDA) radar, is proposed [3]. A frequency offset is introduced to the microwave signal transmitted in each array element. An FDA radar with a uniform stepped frequency offset generates a "S"-shaped beampattern that changes periodically with time. This enables the radar to illuminate a particular spatial region and to distinguish range dependent interference such as clutter. However, due to a uniform stepped frequency offset used in the conventional FDA radar, the range-angle imaging of targets cannot be obtained from the FDA beamformer output [4]. In order to decouple an FDA radar range-angle dependent beampattern, research has been conducted to implement a dot-shaped beampattern rather than a "S"-shaped beampattern [5], [6]. This requires the microwave signal transmitted in each array element to have a nonuniform frequency offset and hence, such radar is called a nonuniform FDA radar.

In a nonuniform FDA radar, the usual amplitude and phase control functions are required to control the sidelobe levels and to steer the beam direction. This can be accomplished via microwave photonic techniques due to the advantages of wide bandwidth, free of electromagnetic interference, reconfigurability, integrate with the fiber optic system, and the ability of large-scale integration. Various microwave photonic based amplitude and phase control techniques have been reported [7]-[9]. However, to our knowledge, there is no microwave photonic system that can simultaneously provide arbitrary controls on the amplitude, frequency and phase of a microwave signal, which is needed for a nonuniform FDA radar.

In this paper, we propose a microwave photonic system that has the ability to control the amplitude, frequency and phase of a microwave signal. It is based on a dual-polarization dual-parallel Mach Zehnder modulator (DP-DPMZM) followed by a phase modulator (PM). Experimental results demonstrate the generation of a 15 GHz microwave signal with a frequency offset in the range of -240.2 kHz to 8.4 kHz and over 22 dB spurious signal suppression. Simulation results show a dot-shaped beampattern can be realized by using a 32-element nonuniform FDA radar with a 15 GHz RF carrier and -240.2 kHz to 8.4 kHz frequency offsets.

II. Topology and Principle

The schematic diagram of the proposed microwave photonic system is shown in Fig. 1(a). A continuous wave (CW) light with an angular frequency of ω_c from a laser diode (LD) is launched into a DP-DPMZM. As shown in Fig. 1(b), the DP-DPMZM consists of two DPMZMs connected in parallel and a 90° polarization rotator (PR) at the output of the bottom DPMZM. Each of the two DPMZMs are formed by two sub-MZMs on each arm of a main MZM. MZM1 and MZM2 in the top DPMZM are driven by a pair of 90° phase difference RF signal with an angular frequency ω_{RF}. MZM1, MZM2 and the main MZM are biased at the null, null and quadrature point respectively so that the top DPMZM generates a single RF modulation sideband with the optical carrier being suppressed [10]. The sub-MZM (MZM4) in the bottom DPMZM is biased at the null point. Therefore, the CW light from the LD only passes through MZM3. The bias voltages (V_{b4} and V_{b6}) into MZM3 and the main MZM of the bottom DPMZM can be designed to control the amplitude and phase of the CW light passing through the bottom DPMZM. The polarization state of the CW at the output of the bottom DPMZM is rotated by 90° via a 90° PR. The DP-DPMZM output electric field is given by

$$E_{DP-DPMZM}(t) \propto e^{j\omega_c t}\left[J_1(\beta_{RF})e^{j\omega_{RF}t}\hat{y}+2\cos\left(\frac{\beta_{b4}}{2}\right)e^{j\left(\frac{\beta_{b4}+\pi}{2}\right)}e^{j\beta_{b6}}\hat{x}\right] \quad (1)$$

where $J_n(x)$ is the Bessel function of nth order of the first kind, $\beta_{RF}=\pi V_{RF}/V_{\pi,RF}$ is the modulation index, V_{RF} is the amplitude of the input RF signal, $V_{\pi,RF}$ is the DP-DPMZM RF port half wave voltage, $\beta_{bn}=\pi V_{bn}/V_{\pi,DC}$, V_{b4} and V_{b6} are the DC voltages applied to the DC port of MZM3 and the main MZM of the bottom DPMZM respectively, $V_{\pi,DC}$ is the DP-DPMZM DC port half wave voltage, and $\hat{x}$ and $\hat{y}$ represent the two orthogonal polarization states. (1) shows the output of the DP-DPMZM consists of a single RF modulation sideband and an optical carrier travelled in the slow and fast of an optical fiber respectively

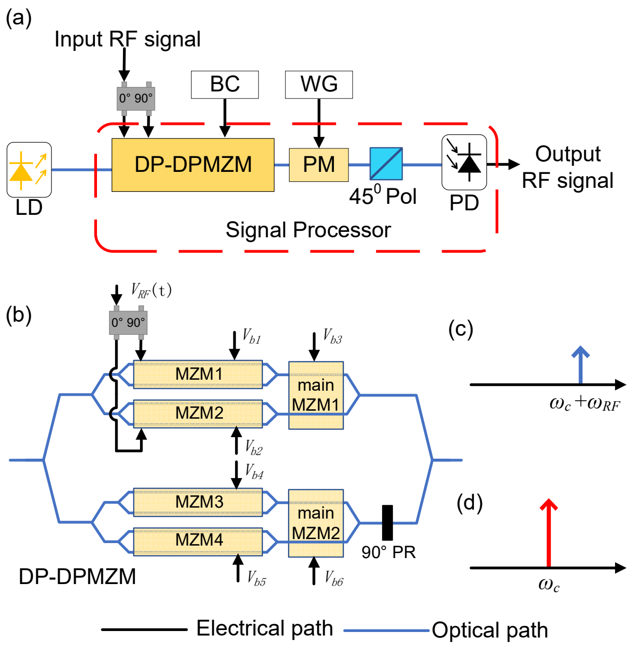

Fig. 1. (a) Schematic diagram of the proposed microwave photonic system. (b) Strcture of a DP-DPMZM . Optical spectrum at the output of the (c) top and (d) bottom DPMZM. LD: laser diode, BC: bias controller, WG: waveform generator, 90° PR: 90° polarization rotator, 45° Pol: 45° polarizer, and PD: photodetector.

A PM is connected to the DP-DPMZM output. It is driven by a sawtooth wave with a period of $1/f_{saw}$ where f_{saw} is the sawtooth wave frequency, for Serrodyne modulation. Note that the modulation efficiency of the light wave in the transverse magnetic (TM) mode is around three times larger than that of the light wave in the transverse electric (TE) mode in a $LiNbO_3$ PM [11]. Hence the RF modulation sideband is efficiently phase modulated by the sawtooth wave as it is travelled in the slow axis and is aligned with the TM mode in the PM. After the PM, the RF modulation sideband is frequency shifted from $\omega_c+\omega_{RF}$ to $\omega_c+\omega_{RF}+\omega_{saw}$, when a sawtooth wave has a positive slope and an amplitude of twice the PM half wave voltage into the PM [12]. Note that a negative frequency shift, i.e. $\omega_c+\omega_{RF}-\omega_{saw}$, can be achieved by using a negative-slope sawtooth wave. A linear polarizer with a transmission axis at a 45° angle between the fast and slow axis is connected to the PM output. This ensures the orthogonally polarized optical carrier and RF modulation sideband passing through the polarizer have the same polarization state. The system output optical signal is detected by a photodetector. A photocurrent is generated and is given by

$$\begin{aligned} I_{PD}(t) &\propto J_1^2(\beta_{RF})+4\cos^2\left(\frac{\beta_{b4}}{2}\right) \\ &+4J_1(\beta_{RF})\cos\left(\frac{\beta_{b4}}{2}\right)\cos\left[(\omega_{RF}+\omega_{saw})t-\left(\frac{\beta_{b4}+\pi}{2}+\beta_{b6}\right)\right] \end{aligned} \quad (2)$$

The last term in (2) shows the system output microwave signal has a frequency offset, which is the same as the sawtooth wave frequency f_{saw}. The amplitude and phase of the system output microwave signal can be controlled via adjusting the modulator bias voltages (V_{b4} and V_{b6}).

Fig. 2 shows an N-element nonuniform FDA radar implemented using an array of the proposed microwave photonic system with a common light source and RF signal source. As shown in the figure, the FDA radar system consists of the processor array, the control signal array and the antenna array. Each processor in the processor array is formed by the components inside the dashed box in Fig. 1(a). The control signal array has a number of modulator bias controllers and waveform generators. Since the frequency offsets required in a nonuniform FDR radar are within ±1 MHz, low-cost and low-frequency waveform generators can be used to generate different-frequency sawtooth waves to obtain the required frequency offsets via Serrodyne modulation. The beampattern spatial location can be steered by adjusting the DC voltages from the modulator bias controllers and the sawtooth wave frequencies from the waveform generators. As the integrated microwave photonic technology becomes mature, the processor array shown in Fig. 2 can be integrated in a single chip. This reduces the size, cost and energy consumption of the system.

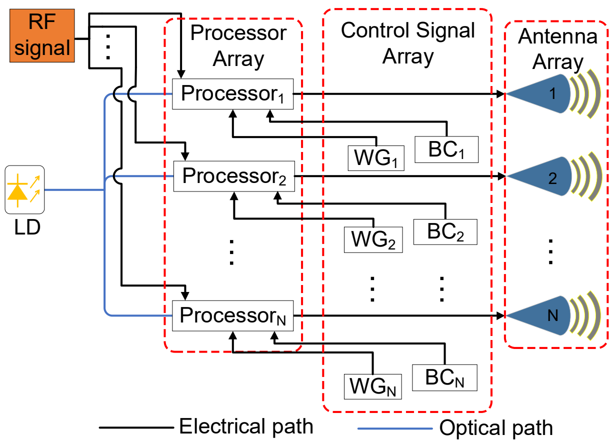

Fig. 2. Topology of the proposed microwave photonic based nonuniform FDA radar system. LD: laser diode, WG: waveform generator, and BC: bias controller.

III. Experimental Results

An experiment is set up based on Fig. 1(a) to verify the concept of the proposed microwave photonic system. A LD (IDPhotonics CoBriteDX1) is used to generate a 1550 nm CW optical carrier with 15 dBm optical power. The DP-DPMZM (Fujitsu FTM7977HQA) has a 3-dB bandwidth of 23 GHz. A polarization controller (PC) is employed between the LD and the DP-DPMZM to align the polarization state of the CW light to the slow axis before launching into the DP-DPMZM. A bias controller (PlugTech MBC-DPIQ-01) is used to provide DC voltages to the MZMs inside the DP-DPMZM so that the MZMs are operated at the desired points in the transfer functions as was discussed in Section II. A 15 GHz RF signal generated by an RF signal generator is split into two portions via a 90° hybrid coupler (Marki microwave QH-0440) before injecting into the two RF ports of the top DPMZM inside the DP-DPMZM. The output of the DP-DPMZM is connected to a PC to align the RF modulation sideband and the optical carrier in the slow and fast axis with the TM and TE mode respectively, in a 10 GHz 3-dB bandwidth PM (Thorlabs LN53S-FC). The PM is driven by a sawtooth wave generated by an arbitrary waveform generator (AWG). The sawtooth wave has a peak-to-peak amplitude of 10 V, which is around twice the PM half wave voltage. A PC and a polarizer are inserted at the PM output. They function as a 45° polarizer to project the orthogonally polarized optical carrier and RF modulation sideband into the same polarization state. The output optical signal is detected by a 20 GHz 3-dB bandwidth photodetector (OE-Space Technologies PIN/TIA20T).

The required frequency offset Δf_n for the microwave signal transmitted by the nth array element of a 32-element nonuniform FDA radar is given by [6]

$$\Delta f_n = \left[(n-1)\log(n+2) - \frac{1}{4}(n-1)^2 \right]\delta \tag{3}$$

where n is the element index and δ is a configuration parameter. Fig. 3 shows the required frequency offsets are in the range of -240.2 kHz to 8.4 kHz. According to (3), the required frequency offset of the 0th array element is -1.886 kHz. A 1.886 kHz negative-slope sawtooth wave is applied to the PM. Fig. 4 shows the system output electrical spectrum measured on an electrical spectrum analyzer (ESA) (Keysight N9020B) connected to the photodetector output. As shown in the figure, the system output microwave signal has a frequency offset of -1.886 kHz away from 15 GHz. The spurious signals are 30.5 dB below the frequency shifted signal. The frequency and the slope of the sawtooth wave into the PM are adjusted to obtain different frequency offsets required for the array elements in the 32-element nonuniform FDA radar. The corresponding system output electrical spectrums are recorded. The frequency offsets found from the output spectrums are shown in Fig. 3. The measurement shows the required frequency offsets for a 32-element nonuniform FDA radar can be obtained using the proposed microwave photonic system. For the frequency offsets between -240.2 kHz and 8.4 kHz, the spurious signals are more than 22 dB below the frequency shifted signal. Note that the amplitude of the sawtooth wave into the PM is fixed at 10 V and is limited by the AWG available for experiment. Larger spurious signal suppression is expected by increasing the sawtooth wave amplitude to ensure it is twice the PM half wave voltage.

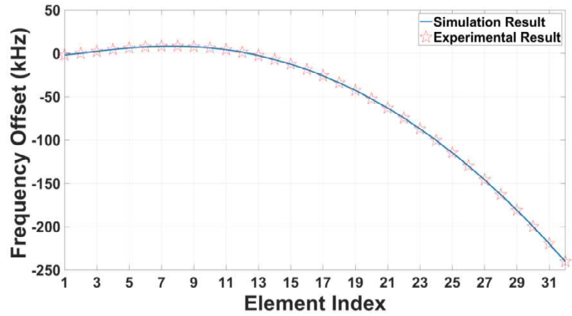

Fig. 3. Measured (star) and simulated (solid line) frequency offsets required for different array elements in a 32-element nonuniform FDA radar. The configuration parameter δ is 2 kHz.

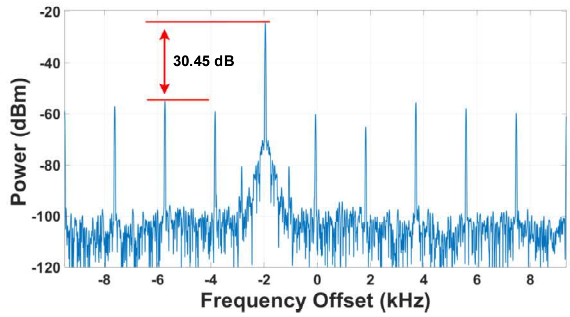

Fig. 4. Electrical spectrum at the output of the proposed microwave photonic system when a sawtooth wave with a frequency of 1.886 kHz and a negative slope is applied to the PM. The center frequency of the spectrum is relative to the input RF signal frequency of 15 GHz.

The beampattern of a 32-element nonuniform FDA radar steered at a particular spatial location (R_T, θ_T) can be expressed as [6]

$$B(t;R,\theta) = \left| \sum_{n=0}^{31} e^{j2\pi\Delta f_n \left(t - \frac{R-R_T}{c}\right)} e^{j2\pi f_{RF} n d \frac{(\sin\theta - \sin\theta_T)}{c}} \right|^2 \tag{4}$$

where t is a reference time, c is the speed of light in vacuum and d is the distance between adjacent array elements in a nonuniform FDA radar. Fig. 5(a) shows the beampattern obtained using (4) together with the measured frequency offsets given in Fig. 3. A single maximum at the target location of (R_T=500 km, θ_T=0°) can be seen. A detailed beampattern at the target location is shown in Fig. 5(b). It can be seen that much of the signal is concentrated around the main lobe. The sidelobes are around 68% below the main lobe.

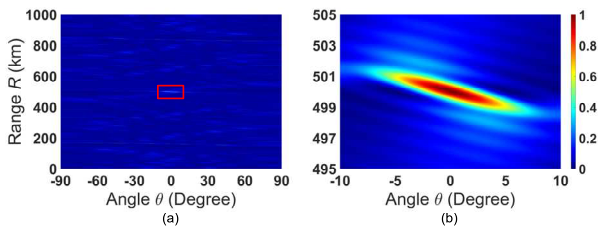

Fig. 5. (a) Normalized beampattern of a 32-element nonuniform FDA radar obtained using the measured frequency offsets shown in Fig. 3. (b) Zoomed-in view of the beampattern inside the red box in (a). The reference time t is 0 s and the distance between adjacent array elements d is 1 cm.

IV. Conclusion and Future Works

A microwave photonic system that has the ability of controlling the amplitude, frequency and phase of a microwave signal has been presented. It has applications on nonuniform FDA radars where the transmitting microwave signal amplitude, frequency and phase need to be controlled to obtain a dot-shaped beampattern to overcome the problem of ambiguity in range-angle localization of targets in conventional FDA radar. The frequency offset of the microwave signal transmitted by the *n*th element in a 32-element nonuniform FDA radar is simulated. Experimental results demonstrate the proposed structure can realize the required frequency offsets with over 22 dB spurious signal suppression, for the FDA radar to generate a dot-shaped beampattern. Future works involve optimizing the system parameters to improve the spurious signal suppression ratio and to verify the ability of amplitude and phase controls of the microwave signal generated by the proposed microwave photonic system.

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