Simultaneous Measurements of Angle of Arrival and Doppler Frequency Shift Based on Silicon Modulators

Sihan Chen[2], Qiang Zhang[1*], Jingyang Fan[2], Xingyi Jiang[2], Shuyue Zhang[2], Hui Yu[1,2]
[1]*Zhejiang Lab, Hangzhou 311121, China*
[2]*College of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China*
**Corresponding author: zhangqiang@zhejianglab.com*

Abstract: We experimentally demonstrate the simultaneous measurements of the microwave angle of arrival and Doppler frequency shift by silicon modulators. The measurement errors of AOA and DFS are less than 3° and 7.2×10^{-10} Hz at 30 GHz, respectively.

1. Introduction

Microwave measurements, such as angle of arrival (AOA) and Doppler frequency shift (DFS) have been widely used in many applications, such as radar detection system, electric warfare system and self-driving. In general, these systems are implemented by electrical devices and technology. Due to the electronic bottlenecks, however, the conventional electrical devices and systems are difficult to implement in a large frequency range from MHz to tens of GHz. To overcome the drawbacks of electrical approaches, microwave measurement of AOA and DFS based on photonic methods have been proposed since the photonic systems support large broad bandwidth, high speed, low loss and immunity to the electro-magnetic interference.

The photonic methods to measure AOA of microwave can be realized by measuring the relative time delay [1] or phase difference [2] between the echo signals from two different antennas. Normally, the measurement of phase difference can be converted to the measurement of the power of optical signal or the intermediate frequency (IF) signal obtained by frequency mixings between the echo signal with the transmitted signal. As for the measurement of microwave DFS, the absolute value can be obtained easily by frequency mixing between transmitted signal and echo signal, thus the researchers pay more attention to distinguish the direction of the DFS. The most utilized method to realize that is by comparing the phase relationship of IF signals in two different channels [3].

However, above mentioned systems can only measure AOA and DFS separately. The measurements of AOA and DFS are needed simultaneously in many situations for obtaining both the direction and velocity of target. Recently, there are many systems to measure AOA and DFS simultaneously are proposed [4]. More importantly, such systems are constructed by discrete optical devices and optical fiber, which have the drawbacks of bulky size, high power consumption, high cost and low stability. Compared with that, silicon photonic technology can realize a high-level integration and have inherent advantages CMOS compatible and potential of seamless integration with electronics [5].

In this paper, we demonstrate a simultaneous measurement system of AOA and DFS based on silicon dual-parallel Mach-Zehnder modulators (Si-DPMZM). One of two echo signal modulates one sub Mach-Zehnder modulators (sub-MZMs). Another echo and transmitted signals are combined to one path and drive another one sub-MZM. Subsequently, the upper and lower sidebands of the output signal are filtered out by a wavelength-division multiplexer (WDM) and sent to two photodiodes (PDs). After the analysis of amplitudes and phases of the IF signals from two PDs, the information of AOA and the DFS can be obtained. A proof-of-concept experiments at 30 GHz are carried out. The measurement errors of AOA and DFS are less than 3° and 7.2×10^{-10} Hz, respectively.

2. Principle

Fig.1 shows the schematic diagram of the proposed measurement system. An optical carrier $E(t)=E_0\exp(j\omega_0 t)$ from a laser diode is generated by a laser diode (LD) and sent to the Si-DPMZM via a polarization controller (PC). The optical carrier is split into two sub-MZMs (MZM-1/2) by an on-chip thermal-optic 1×2 optical power splitter (TOPS) and then modulated by the echo signal and transmitted-echo combined signal. Both two sub-MZM are push-pull configuration with two series PN junction and operated at minimum point. Subsequently, the upper and lower sides of output optical signal of Si-DPMZM is separated by two-channel WDM and detected by the corresponding PDs. the optical currents from the PD1/2 can be expressed as Eqs. (1) and (2).

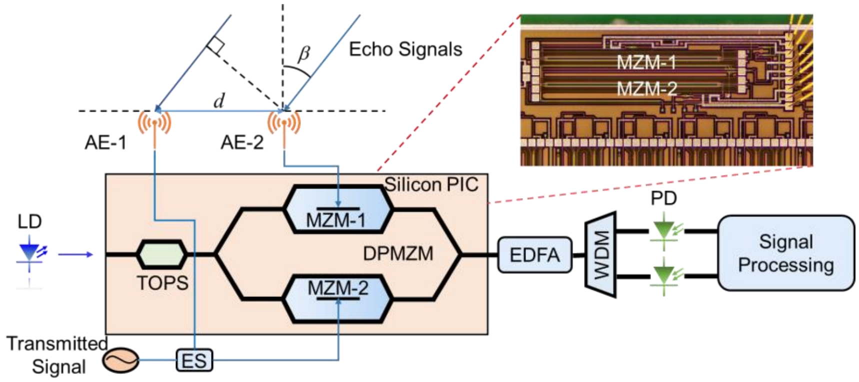

Fig.1 Schematic diagram of the proposed system for DFS and AOA measurements. AE: Antenna element, LD: laser diode, TOPS: thermal-optic optical power splitter; PD: Photodiode, DPMZM: Dual-parallel Mach-Zehnder modulator, EDFA: Erbium doped fiber amplifier, WDM: wavelength-division multiplexer, ES: electrical synthesizer.

$$I_U(t)=\eta\frac{E_0^2}{4}J_1(m_E)J_1(m_T)\sqrt{A^2+B^2}\cos\left[(\omega_E-\omega_T)t+\arctan\frac{B}{A}-(\varphi_2+\theta)\right] \tag{1}$$

$$I_L(t)=\eta\frac{E_0^2}{4}J_1(m_E)J_1(m_T)\sqrt{C^2+D^2}\cos\left[(\omega_E-\omega_T)t-\arctan\frac{D}{C}+(\varphi_2+\theta)\right] \tag{2}$$

Here, η denotes the responsivity of the PD, m_E and m_T are the modulation indexes of MZM-1 and MZM-2, respectively. A, B, C, D can be calculated by $A=\cos(\varphi_1)+J_0(m_T)\cos(\varphi_2+\theta+\varphi)$, $B=\sin(\varphi_1)+J_0(m_T)\sin(\varphi_2+\theta+\varphi)$, $C=\cos(\varphi_1)+J_0(m_T)\cos(\varphi_2+\theta-\varphi)$; $D=\sin(\varphi_1)+J_0(m_T)\sin(\varphi_2+\theta-\varphi)$. ω_E and ω_T denote the angular frequencies of echo and transmitted signals, respectively. $\varphi_{1/2}$ and θ are the bias phases of MZM-1/2 and parent MZM, respectively. m_E and m_T represent the modulation index caused by the transmitted and echo signal, respectively. Furthermore, $\varphi_{1/2}=\pi$ for carrier-suppressed double side modulation. φ denotes the phase delay of two echo signals. With the aid of above equations, the phase difference between $I_U(t)$ and $I_L(t)$ can be calculated as arctan(B/A)+arctan(D/C)–2($\varphi_2+\theta$) or –[arctan(B/A)+arctan(D/C)–2($\varphi_2+\theta$)] when $\omega_E>\omega_T$ or $\omega_E<\omega_T$. According this relationship of the two IF signals in two channels, the direction of DFS is obtained.

According to the theory of quadratic detection, the electrical power of DFS signals in two channels (upper/lower channel) can be deduced as:

$$P_U=\eta^2\frac{E_0^4}{16}J_1^2(m_E)J_1^2(m_T)\left[1+J_0^2(m_T)+2J_0(m_T)\cos(\varphi+\theta)\right] \tag{3}$$

$$P_L=\eta^2\frac{E_0^4}{16}J_1^2(m_E)J_1^2(m_T)\left[1+J_0^2(m_T)+2J_0(m_T)\cos(\varphi-\theta)\right] \tag{4}$$

From Eqs. (3) and (4), the electrical power-phase mapping curves of DFS in two channels can be obtained. By comparing the normalized values of the two DFS signal power, the value of φ can be ensured. After that, AOA of β can be measured based on $\beta=arcsin(\varphi c/d\omega_E)$. Here, c is the velocity of light. d denotes the distance of two receiving antennas, usually the half of the received signal's wavelength.

3. Experiment and results

An experiment based on Fig.1 is carried out. The image of the silicon photonic integrated chip (PIC) is shown in the inset of the Fig.1. The LD generates an optical signal with wavelength of 1550 nm and output power is 14 dBm. The optical signal is coupled into and out of the silicon PIC via grating coupler. The PC that placed before PIC is used to tune the polarization state of optical signal for reducing the polarization-dependent optical loss. In the experiment, the transmitted signals at 30 GHz is generated by RF source (Keysight E8267D) while the echo signal at 30 GHz +/– 1 MHz is generated by another one same RF source. Two RF sources are synchronized by a 10 MHz signal. The echo signal is divided into two paths, one modulates MZM-1 while another one is combined with transmitted signal to modulate MZM-2. An electrical phase shifter is used to tune the phase difference of two echo signals. The reverse bias voltages of two sub-MZMs are set to be -2V for operation at carrier-depletion condition. Three DC sources are used to control the bias conditions of the two sub-MZMs and parent MZM.

Fig.2 (a)/(b) presents the electrical waveforms of DFS signals at 1 MHz in two channels measured by a 100 MHz bandwidth digital oscilloscope. Two IF signals in lower channel (L-channel) and upper channel (U-channel) have a relative phase delay. When the DFS signal in L-channel is ahead of the upper one, the direction of DFS is negative that is shown in Fig.2 (a); otherwise, the direction of DFS is positive that is shown in Fig.2(b). Furthermore, the measurement errors from 0 to 100 kHz with step 10 kHz is given in Fig. 2(d) whose values are less than 7.2×10^{-10} Hz.

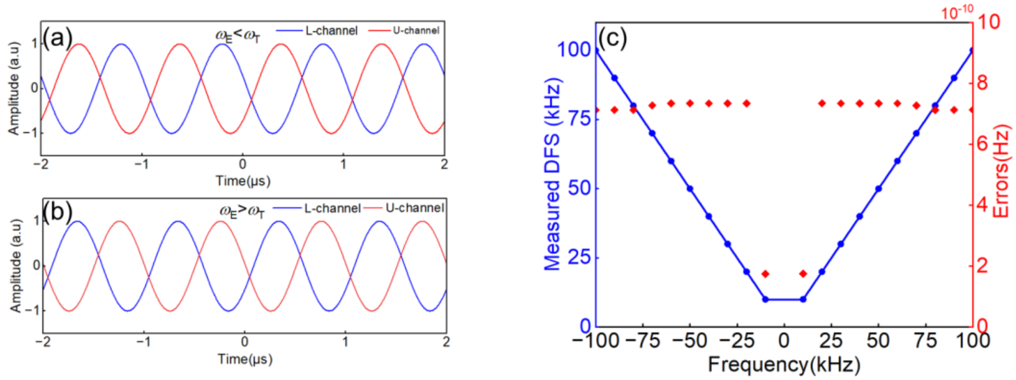

Fig.2 The normalized electrical waveforms of two different channels with directions of (a) negative and (b) positive. (c) Measured DFS frequency (blue) and measured errors (red) at 30 GHz.

To verify the scheme of measuring AOA, we adjust the phase difference between the two echo signals by an electrical phase shifter and measure them in the range from 0° to 360°. The normalized electrical power versus phase shift (φ) of two channels from 0° to 360° are illustrated as Fig. 3(a). The red/blue curve represents the relationship of upper/lower channel. The distance between the two curves is about 70°, which indicates the bias of the parent MZM is about 35°. By comparing these two curves, the AOA of target can be obtained. The measurement errors of AOA are given in Fig, 3(b), which are less 3°.

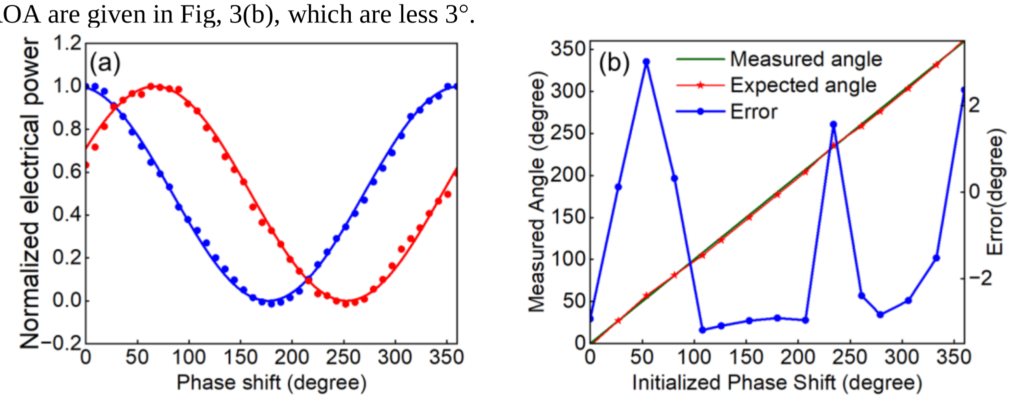

Fig.3 (a) The measurement results of AOA. Experimental results data(dots) and the fitting curve (line). (b) Measurement errors of AOA at 30 GHz.

3. Conclusion

In this work, we demonstrate a measurement system of simultaneous measuring DFS and AOA based on silicon integrated modulators. By measuring the frequency difference between the echo signal and transmitted signal, the DFS can be obtained by measuring the beating frequency. In the proposed measurement system, two echo signals interfere in optical domain and build two power mapping curves for obtaining AOA. The measurement errors of DFS and AOA at 30 GHz are less than 3° and 7.2×10^{-10} Hz at 30 GHz, respectively.

4. References

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