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Zhaoyang Tu
Aijun Wen, *Senior Member, IEEE*
Zhongguo Xiu
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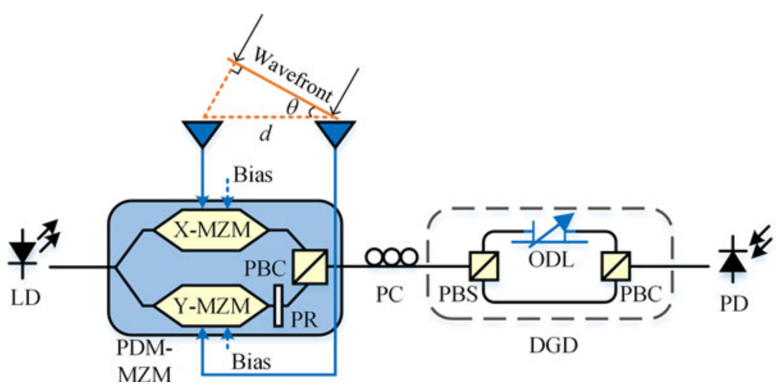
Mei Chen



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Angle-of-Arrival Estimation of Broadband Microwave Signals Based on Microwave Photonic Filtering

Zhaoyang Tu,[1, 2] **Aijun Wen,**[1, 2] ***Senior Member, IEEE,***
Zhongguo Xiu,[1, 2] **Wu Zhang,**[1, 2] **and Mei Chen**[1]

[1]State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an 710071, China
[2]Collaborative Innovation Center of Information Sensing and Understanding at Xidian University, Xi'an 710071, China

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Abstract: We propose and experimentally demonstrate a photonic approach to estimate the angle-of-arrival (AOA) of broadband microwave signals. Using an integrated polarization-division multiplexing Mach–Zehnder modulator and a differential group-delay module, a microwave photonic notch filter is constructed. The relative time delay in reception of the signal at two separate antenna elements can be obtained by measuring the transmission notches over the signal spectra. The AOA is calculated from the relative time delay and the antenna spacing. The experiment results show that the measurement error is less than ± 0.35 ps when the relative time delay changes from -14 to 16 ps.

Index Terms: Angle of arrival, microwave photonic filter, microwave photonics, differential group delay.

1. Introduction

The ability to accurately estimate the angle-of-arrival (AOA) of an incoming signal is often required in a wide range of applications such as broadband mobile systems, radar systems and electronic warfare [1], [2]. However, AOA estimation of microwave signals with high frequency and large instantaneous bandwidth is a critical challenge for electronic devices. Thanks to the inherent merits of large time-bandwidth product and immunity to electromagnetic interference [3], [4], numerous innovative photonic techniques have been conducted to address microwave measurements [5], [6].

So far, a few photonic AOA estimation approaches have been reported [7]–[13]. Among these approaches, the basic principle of determining the AOA of an incoming signal is to measure the phase shift or relative time delay between the radio frequency (RF) signals received at two separate antenna elements. In [7], the microwave signal and its phase delay replica received at two antennas are applied to two electro-optical modulators, and the AOA can be derived from the

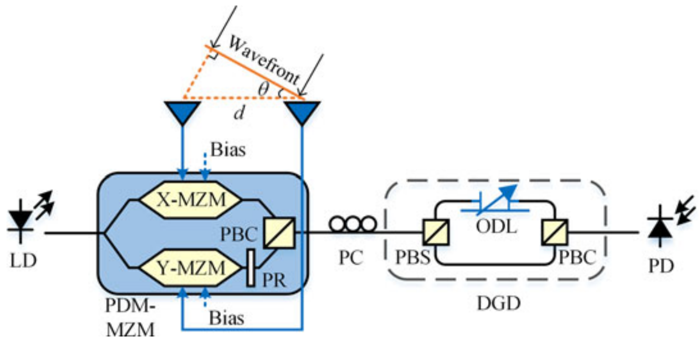

Fig. 1. Schematic diagram of the proposed system. LD: laser diode; PDM-MZM: polarization division multiplexing Mach–Zehnder modulator; DGD: differential group-delay module; PBC: polarization beam combiner; PC: polarization controller; PBS: polarization beam splitter; ODL: optical delay line; PR: polarization rotator; PD: photodetector.

phase shift which is obtained by measuring the optical carrier power. In addition, parallel optical delay structures are proposed utilizing a dual-parallel Mach-Zehnder modulator (DP-MZM) [8] or a dual-drive MZM [9]. By suppressing the optical carrier, the phase delay can be obtained by measuring the optical sidebands power. However, power fluctuations of the laser source or bias drifting of the modulator due to the environment variations (e.g., temperature) would be reflected in phase shift measurement, which may degrade the measurement accuracy. In addition, the AOA can be obtained by means of a pair of microwave photonic down-converters [10], [11]. In this way, the time delay between the microwave signals can be obtained by measuring the time delay between the corresponding intermediate frequency (IF) signals.

However, the approaches based on phase detection can only be used for pure single-tone signal and the approaches based on down-conversion require further IF processing. Therefore, their ability to process signals with large instantaneous bandwidth is limited. One method based on spectral hole burning effect in spatial-spectral materials [12] is capable of processing broadband signals, but this approach requires operation at cryogenic temperatures. In [13], an AOA estimation system based on photonic microwave filtering is proposed in which the time delay of the broadband signal can be obtained by measuring the transmission notch. However, two laser sources operating at different wavelengths and a pair of intensity modulators are needed which would increase system complexity. In addition, the power fluctuation of the two laser sources [14] would degrade the notch rejection level, which impacts the measurement accuracy.

In this paper, a novel photonic AOA estimation scheme for broadband microwave signals is proposed and experimentally demonstrated. Using a polarization division multiplexing Mach-Zehnder modulator (PDM-MZM) and a differential group-delay (DGD) module, a transversal microwave photonic notch filter is firstly implemented. The AOA of an incoming signal can be estimated from the relative time delay which is obtained by measuring the transmission notch. Different from [13], the electrical to optical conversions of the two received signals are implemented in a single integrated modulator whose outputs are orthogonally polarized. By means of a DGD module, a relative time delay between the two orthogonal polarizations is introduced. In this way, a two-tap microwave photonic filter is constructed and the limitation due to the optical coherence can also be removed thanks to orthogonal polarizations [15]. Compared with [13], the proposed scheme requires only one laser source and one modulator, which can improve system stability and reduce system cost. Furthermore, the proposed scheme is insensitive to the power fluctuation of the laser source.

2. Operation Principle

Fig. 1 illustrates the proposed AOA estimation scheme. Two antenna elements are placed with a spacing of d and the two received RF signals have a relative time delay depending on the direction of the emitter. In a far-field scenario, distances from the emitter to the antenna elements is in orders of the magnitude of d. The AOA can be given by

$$\theta = \sin^{-1}\left(\frac{c \cdot \Delta\tau}{d}\right) \tag{1}$$

where c is the speed of light in vacuum, $\Delta\tau$ is the relative time delay between the signals received at two separate antenna elements.

Thus, the AOA estimation is corresponded to time delay measurement as we know the antenna spacing. The time delay measurement system presented here is based on photonic microwave filtering [13]. The principle of operation is described as follows.

The system consists of a laser diode (LD), an integrated PDM-MZM, a polarization controller (PC), a DGD module, and a photodetector (PD). A light wave generated from the LD is sent to the PDM-MZM via polarization maintaining fiber (PMF). The PDM-MZM [16], [17] is a commercially available electro-optical modulator which can be used for dual-polarization binary phase-shift keying modulation in digital optical communications. It includes a Y-splitter, two parallel sub-MZMs, a 90° polarization rotator and a polarization beam combiner (PBC). In the PDM-MZM, the incident light wave is divided into two equal portions, and then sent to two sub-MZMs, respectively. Meanwhile, the received RF signals from the two separate antenna elements are applied to the respective RF ports of the two sub-MZMs. After the 90° polarization rotator following the Y-MZM, the parallel modulated optical signals become orthogonally polarized. Then, the two polarizations are combined by the PBC, and sent to a DGD module through a PC. When the PC is properly adjusted, the two orthogonal polarizations are oriented at the slow and fast axis of the DGD module, respectively. In this way, a relative time delay is introduced between two orthogonal polarizations. Commercially available polarization-mode dispersion emulator (PDME) [18] can provide variable DGD values. Then, the output optical signal from the DGD module is sent to the PD. Thus, a two-tap filter is obtained, and its frequency response is given using the well-known equation

$$H\,(f) = \sum_{n=0}^{1} a_n e^{-j2\pi nf(\tau+\Delta\tau)} \tag{2}$$

where a_n ($n = 0, 1$) is the tap coefficient. τ is the initial time delay exists in the system and it can be changed by means of the DGD module. $\Delta\tau$ denotes the relative time delay depending on the AOA.

When the two sub-MZMs are separately biased at positive and negative quadrature transmission point, two DSB signals with phase inversion are generated [19], and we have $a_0 = -a_1$. As a result, a microwave photonic filter with negative coefficient is constructed.

The notch filter has a periodic amplitude response and its free-spectral range (FSR) is

$$FSR = \frac{1}{\tau + \Delta\tau} \tag{3}$$

In addition, the frequency notches can be expressed as

$$f_{notch} = \frac{k}{\tau + \Delta\tau} \tag{4}$$

where $k = 0, 1, 2\ldots$

As shown in the Fig. 2, the notch filter is tuned when the $\Delta\tau$ changes. By measuring the notch frequency, $\Delta\tau$ can be calculated based on (4). However, only the frequency notches within the bandwidth range of the incoming broadband signal can be observed. Thus, before the measurement, the initial time delay has to be adjusted to match with the incoming microwave signal. When the initial time delay is properly adjusted, the relative time delay between the two signals received at the two separate antenna elements can be calculated by

$$\Delta\tau = \frac{k}{f_{notch}} - \tau \tag{5}$$

where f_{notch} can be measured by means of a network analyzer or microwave photonic filters [13].

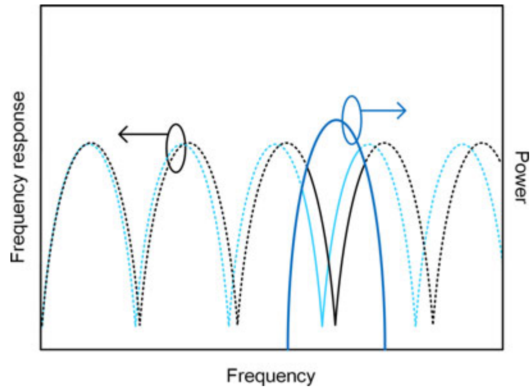

Fig. 2. Concept of the proposed AOA measurement system. The solid line depicts power spectra of the incoming signal. The dotted lines depict the responses of the original filter (in black) and the filter with a different $\Delta\tau$ (in blue).

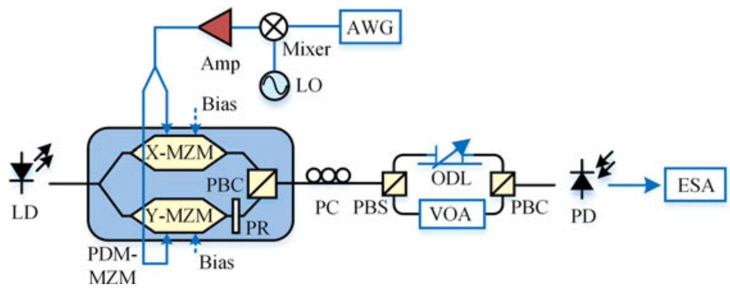

Fig. 3. Experimental setup of the proposed AOA estimation system. LD: laser diode; PDM-MZM: polarization division multiplexing Mach-Zehnder modulator; PR: polarization rotator. AWG: arbitrary waveform generator; LO: local oscillator; Amp: electrical amplifier; PBC: polarization beam combiner; PC: polarization controller; PBS: polarization beam splitter; ODL: optical delay line; VOA: variable optical attenuator; PD: photodetector; ESA: electrical signal analyzer.

For simplicity, let the frequency of the *k*-th notch equal to the central frequency of the incoming signal. The frequency offset of the *k*-th notch is given by

$$\Delta f = f_{notch} - f = -\frac{f \times \Delta\tau}{\tau + \Delta\tau} \tag{6}$$

where f is the central frequency of the incoming signal. Considering τ is much greater than $\Delta\tau$ in the proposed system, we can see from (6) that τ determines the system sensitivity. For instance, when reducing the initial time delay, the frequency offset would have a faster change rate versus the relative time delay. As a result, the measurement accuracy is improved. However, the corresponding measurement range becomes smaller, since only the notches within the bandwidth of the incoming signal are visible.

To avoid ambiguity, the notch offset should not exceed the filter FSR. As a result, the measurement range is limited by the bandwidth of the incoming signal and the FSR of the filter. It can also be seen from (6) that negative $\Delta\tau$ would result in increased notch frequency and vice versa for positive $\Delta\tau$. Therefore, the ambiguity between negative and positive AOA can be directly discriminated in the proposed scheme.

3. Experiment and Discussion

An experiment for AOA estimation is performed according to the setup in Fig. 3. A light wave at around 1552 nm is generated from an LD (Emcore 1782) with a power of 12 dBm, and sent to a PDM-MZM (Fujitsu, FTM7980EDA) via PMF. A 1.6 Gbps non-return-to-zero signal is generated

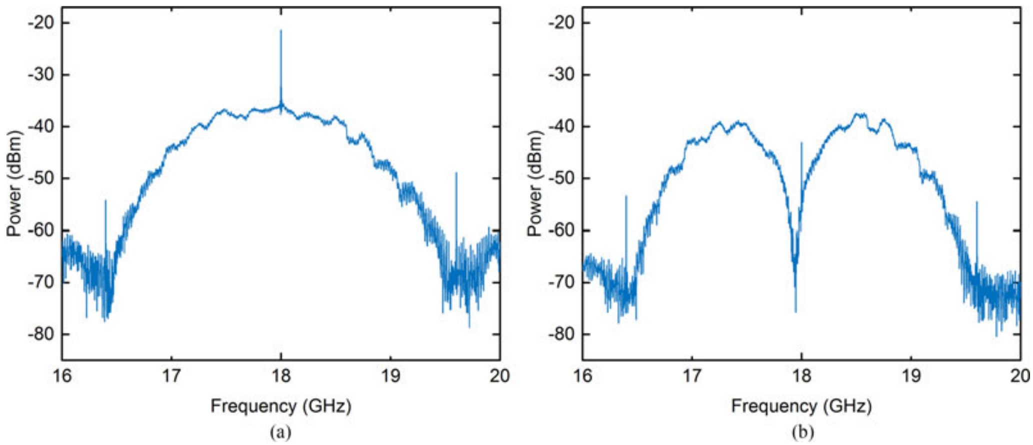

Fig. 4. Spectra of the (a) unfiltered and (b) filtered broadband signal.

from an arbitrary waveform generator (Tektronix, AWG7082C) and mixed with an 18-GHz local oscillator (LO) signal from a microwave signal generator (Agilent, N5183A). After the electrical amplifier, the signal is divided into two equal portions to emulate the two replicas of the incoming signal. Then, the signals are applied to the RF ports of two sub-MZMs of the PDM-MZM modulator, respectively. The modulator insertion loss is about 6 dB, and the switching voltages are about 3.5 V. Since the PDME is not available in our lab, an optical delay line (ODL, General Photonics, MDL002) which has a tuning resolution of 1 fs is employed in the following measurement. After modulation, the optical signal is sent to a PBS via a PC. By adjusting the PC, the polarization multiplexed optical signal can be precisely polarization demultiplexed. The ODL is employed in the upper branch, while a variable optical attenuator (VOA) is used in the lower branch to minimize the power difference between the two branches. Then, we combine the two optical signals utilizing a PBC and send it to a wideband PD (U2T, DPRV2022A). Since the pigtails of the PBS and PBC used in the experiment are both PMFs, the combination is stable and don't need the use of PCs. The detected electrical spectrum is analyzed by an electrical signal analyzer (Rohde & Schwarz, FSW50).

Fig. 4(a) illustrates the power spectra of the unfiltered broadband signal and the resolution bandwidth (RBW) of the electrical signal analyzer is 1 MHz. By adjusting the ODL in the upper branch, the seventh notch is selected for AOA estimation. It can be seen from Fig. 4(b) that the notch is located at around 18 GHz which is the central frequency of the broadband signal. It is better to change the AOA for the measurement accuracy test. However, due to equipment limitation, the change of AOA is emulated by means of altering the time delay introduced by the ODL [7], [13]. In the same time, the notch frequency corresponding to the different relative time delay is measured. In this way, two sets of measurements are carried out. To determine the initial time delay between the two branches, the first measurement results are used for calibration. The measured frequency offsets and the corresponding time delay are depicted in Fig. 5. By manually selecting the parameters to match with the measurement results, we have $\tau = 390.05$ ps and $k = 7$. In practice, the least squares method can be used. Based on the calibration results, the theoretical curve as a function of frequency offset is plotted. An acceptable agreement is obtained. It can be seen from Fig. 5, with a larger slope, a fixed frequency measurement error would lead to larger time delay measurement error. As an important parameter that affects measurement performance, the slope of the theoretical curve is calculated to be –21.2 ps/GHz.

After calibration, the estimated relative time delay can be calculated from measured frequency offsets based on (5). Fig. 6 shows the measurement results and corresponding measurement errors. The measurement errors for relative time delay are less than ± 0.35 ps. In [13], the measurement error is less than 0.9 ps and the slope of the theoretical curve as a function of frequency offset is 133.37 ps/GHz. Thanks to the smaller absolute value of slope used in our system, the measurement accuracy is improved.

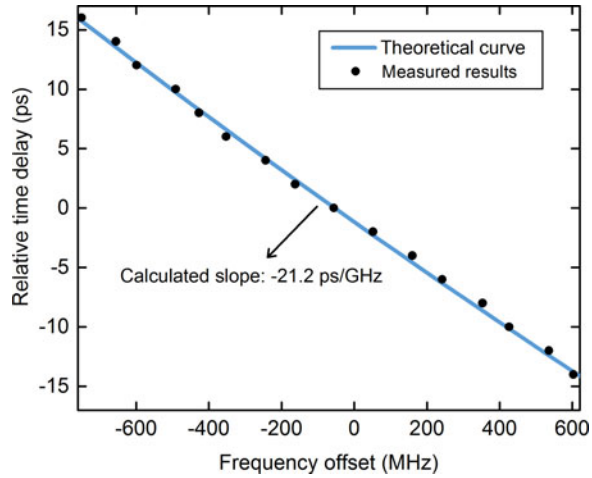

Fig. 5. Measured frequency offset values versus relative time delay.

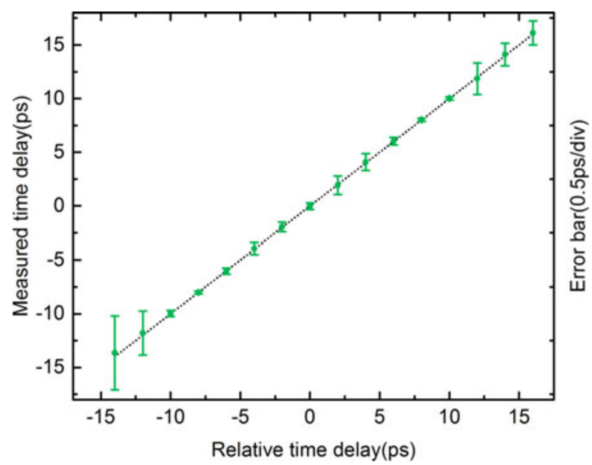

Fig. 6. Measured relative time delay (dots) and the corresponding measurement errors (vertical bars).

Assuming an antenna spacing of $\lambda/2$, the AOA measurement error is less than 0.72° at the boresight. The time delay measurement range is from –14 ps to 16 ps, which corresponds to a field of view of –30.26° to 35.17°. According to the theoretical analysis in Section 2, the measurement range can be extended by choosing a larger initial time delay, but reduced measurement accuracy is expected. Since the principle of proposed system is based on frequency domain measurement, multi-emitter can be resolved. When there exists only one frequency notch over each signal spectra, the AOA of each emitter can be calculated from their corresponding frequency notch.

In practice, the received RF signal is always accompanied by noise, and a minimum acceptable signal-to-noise ratio (SNR) is required. Based on our simulation, a minimum SNR of 19.2 dB at 1 MHz spectral resolution can ensure that the measurement error is less than $\pm$0.35 ps in the proposed system.

In the proposed scheme, the intrinsic notch rejection level of the two-tap filter can be expressed as

$$NR = \left(\frac{a_0 - a_1}{a_0 + a_1}\right)^2 \tag{7}$$

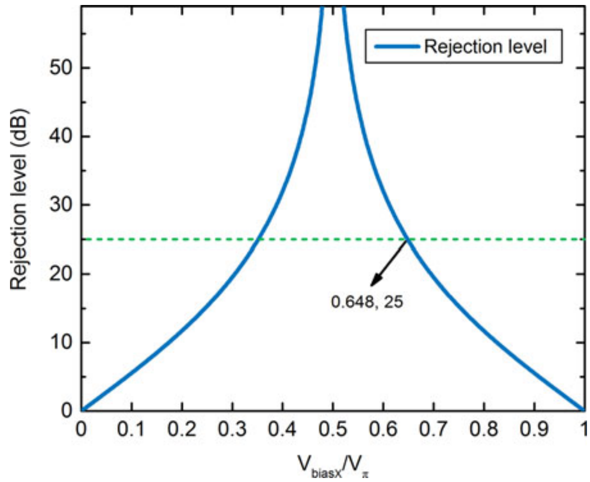

Fig. 7. Calculated intrinsic notch rejection level degradation owing to modulator bias drifting.

The notch has an infinite rejection level when assuming $a_0 = -a_1$. However, bias drifting of the modulator would degrade the rejection level of the notch filter, which impacts the measurement accuracy. Theoretical analysis is shown as follows.

The input light wave can be expressed as $E_{in}(t) = \sqrt{P_{in}}e^{jw_c t}$, where P_{in} and ω_c are its optical power and angular frequency, respectively. The optical field at the output of X-MZM is given by

$$E_X(t) = \frac{\sqrt{2P_{in}}}{4}\left[1 - \exp\left(j\pi V_{RF}(t)/V_\pi + j\pi V_{biasX}/V_\pi\right)\right]e^{j\omega_c t} \tag{8}$$

where V_π is the switching voltage, V_{biasX} is the X-MZM bias voltage and $V_{RF}(t)$ is the modulating RF signal. After the PD, the photocurrent is given by

$$i_X(t) = \Re|E(t)|^2 = \frac{\Re P_{in}}{4}\left[1 - \cos\left(\pi V_{RF}(t)/V_\pi + \pi V_{biasX}/V_\pi\right)\right] \tag{9}$$

where $\Re$ is the responsivity of the PD. Note that the insertion loss of the optical system is neglected for the sake of simplicity. Expanding (9) and using small signal modulation approximation, the photocurrent can be rewritten as

$$i_X(t) \approx \frac{\pi \Re P_{in}}{4V_\pi}\sin\left(\frac{\pi V_{biasX}}{V_\pi}\right)V_{RF}(t) \tag{10}$$

where the direct current and high order terms are neglected. The tap coefficient a_0 can be expressed as

$$a_0 = \frac{\pi \Re P_{in}}{4V_\pi}\sin\left(\frac{\pi V_{biasX}}{V_\pi}\right) \tag{11}$$

Similar to (11), the tap coefficient a_1 is given by

$$a_1 = \frac{\pi \Re P_{in}}{4V_\pi}\sin\left(\frac{\pi V_{biasY}}{V_\pi}\right) \tag{12}$$

where V_{biasY} is the Y-MZM bias voltage. To perform the bias-tolerant test, we let the V_{biasY} equal to $-V_\pi/2$ and the notch rejection level can be expressed as

$$NR = \left[\frac{sin\left(\pi V_{biasX}/V_\pi\right) + 1}{sin\left(\pi V_{biasX}/V_\pi\right) - 1}\right]^2 \tag{13}$$

For the AOA measurement system, the unsuppressed signal at notch position can be considered as system noise. Thus, the notch rejection level should be greater than the minimum required SNR.

Fig. 7 shows the intrinsic notch rejection level curve as a function of V_{biasX}/V_{π}. It can be seen that the rejection level exceeds 25 dB when the bias voltage ranges from $0.352V_{\pi}$ to $0.648V_{\pi}$. Thus, the AOA measurement with a measurement error less than $\pm$0.35 ps can be ensured when the bias drift is within $-$14.8–14.8%. Although the system is stable in operation during the experiment, it should be noted that the bias drifting problem has to be considered for long-term stability. A commercially available modulator bias controller can be used to solve the problem.

According to the above discussion, the AOA is derived from the notch frequency whose measurement accuracy is sensitive to both notch rejection level and system noise.

4. Conclusion

In summary, a photonic approach to estimate the AOA of broadband signals is proposed and experimentally demonstrated. By means of a microwave photonic notch filter, the relative time delay between the two signals received at two separate antenna elements can be obtained by measuring the transmission notches. The relative time delays from –14 ps to 16 ps are measured with the measurement error less than $\pm$0.35 ps. Assuming the $\lambda/2$ antenna spacing, the corresponding AOA is range from –30.26° to 35.17°. Furthermore, the measurement range can be further increased by choosing a larger DGD value. The proposed scheme requires only one laser source and a single integrated electro-optical modulator, thus is stable and compact.

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