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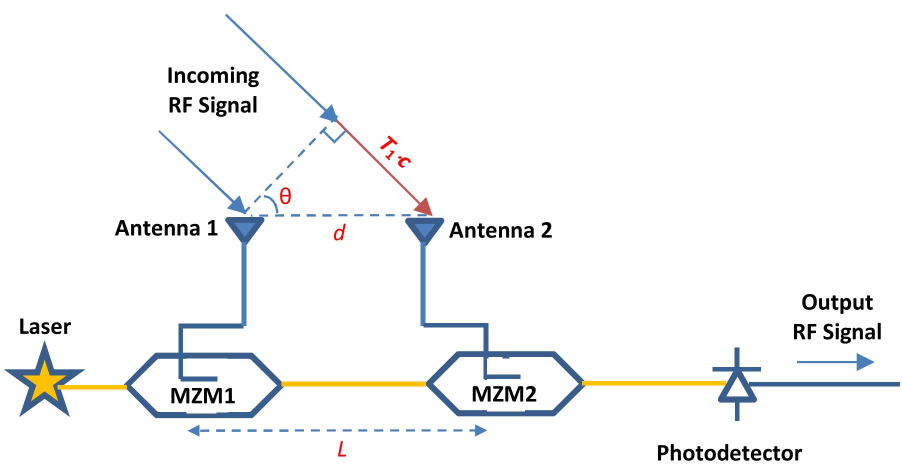

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Angle-of-Arrival Measurement System Using Double RF Modulation Technique

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Abstract: A new technique for determining the angle of arrival (AoA) of an RF signal is presented. It is based on a cascaded modulator structure, where continuous wave light from an optical source is modulated by an incoming RF signal twice. The AoA of an RF signal can be determined by the system output RF signal power. The proposed structure is capable for measuring the AoA of both narrow and broadband RF signals. This overcomes the limitation in all previously reported photonics-based AoA measurement systems, which are applicable to either a single-frequency RF signal or a broadband RF signal. It also does not involve electrical components and high extinction ratio modulators, which are required in reported structures. Experimental results are presented that show an AoA measurement range of 0° to over 65° with errors of less than 1.9° for a microwave signal at 2.65 and 12.62 GHz. Results also show that the system is capable to measure the AoA of a pseudorandom binary sequence signal at a microwave frequency.

Index Terms: Direction-of-arrival estimation, phased arrays, microwave photonics, notch filters.

1. Introduction

Applying photonic technology to phased arrays for radar and communication systems has been studied extensively in the past 30 years. This is because photonics based phased array antenna systems have unique features of wide instantaneous bandwidth, low transmission loss for data remoting, immunity to electromagnetic interference, reconfigurability, small size and light weight [1], [2]. Other than signal transmission and processing, photonic techniques for measuring various parameters of an RF signal received by a phased array antenna system have been developed [3], [4]. One of the measurement parameters is the angle of arrival (AoA) of the incoming RF signal. Direction finding is important for both defence [5] and telecommunication [6], e.g., to discover the location of military radio transmitter and to identify the location of a mobile phone placing an emergency call.

An early reported photonics based direction finding system is based on using microwave photonic downconverters to down convert the incoming RF signal received by different antennas into low-frequency IF signals [7]. The AoA can be obtained by using phase detectors and a digital signal processor to measure and process the phase differences of the IF signals. This technique relies on using electrical components to determine the AoA of an RF signal, which limits the RF signal bandwidth. This problem can be overcome by using an optical delay line structure to generate notches in the signal spectrum and the AoA can be determined based on the notch frequency

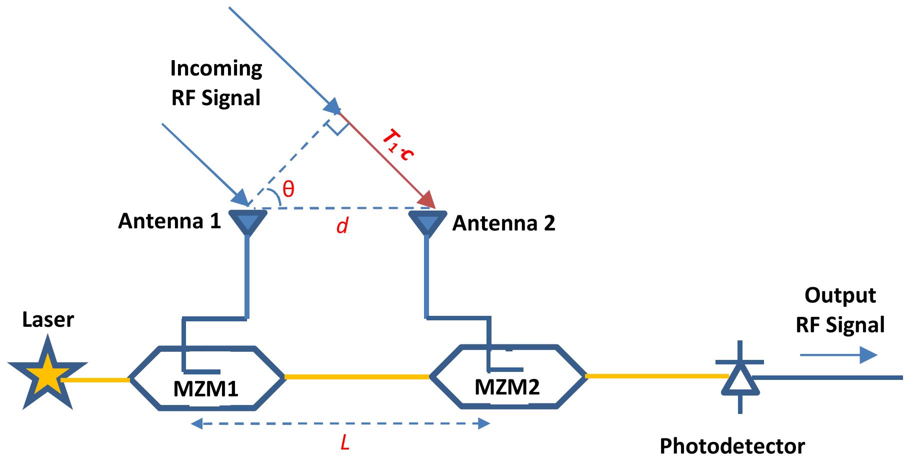

Fig. 1. Schematic diagram of the proposed AoA measurement system.

[8], [9]. The demerit of this technique is that it is only suitable for an RF signal with a broad bandwidth as the AoA measurement range is dependent on the RF signal bandwidth. Measuring the power of the RF modulation sidebands [10] or the optical carrier [11] to determine the AoA involve only optical components and eliminate the requirement of the incoming RF signal to have a wide instantaneous bandwidth. However, they require high extinction ratio optical modulators and an optical filter implemented by a fibre Bragg grating or an arrayed waveguide grating to select either the RF modulation sidebands or the optical carrier. The use of an optical filter limits the system RF signal operating frequency range. Furthermore, a tight control on the wavelengths of the optical source and the optical filter is needed. Therefore these AoA measurement techniques were only demonstrated for a single frequency input RF signal, which generates RF modulation sidebands far away from the optical carrier.

This paper presents a direction finding system based on modulating continuous wave (CW) light twice with a time delay depending on the incoming RF signal AoA, which results in an AoA dependent output RF signal power. An electrical power meter can be used to measure the system output RF signal power to determine the AoA. This technique does not require the RF signal to have a broad bandwidth. Its performance is independent to the modulator extinction ratio and is insensitive to the laser wavelength. Experiments have been carried out that demonstrate 0° to over 65° AoA measurement range with around 2° errors for both a single frequency microwave signal and a pseudorandom binary sequence (PRBS) signal at a microwave frequency.

2. Double RF Modulation Based AoA Measurement System

The structure of the proposed AoA measurement system is shown in Fig. 1. The incoming RF signal arrives at the two antennas separated by a distance d at different times depending on the location of the transmitter. For example Fig. 1 shows the incoming RF signal arrived at Antenna 2 has a time delay τ_1 compared to that arrived at Antenna 1. This time delay causes a phase difference φ_1 between the RF signal arrived at the two antennas, which can be expressed as

$$\varphi_1 = \tau_1 \times \omega_{RF} \tag{1}$$

where ω_{RF} is the angular frequency of the incoming RF signal. The AoA θ is defined as

$$\theta = \sin^{-1}\left(\frac{\tau_1 c}{d}\right) \tag{2}$$

where c is the velocity of electromagnetic radiation in air. The antenna separation is normally designed to be $\lambda/2$, where λ is the incoming RF signal wavelength, to avoid the grating lobes in the

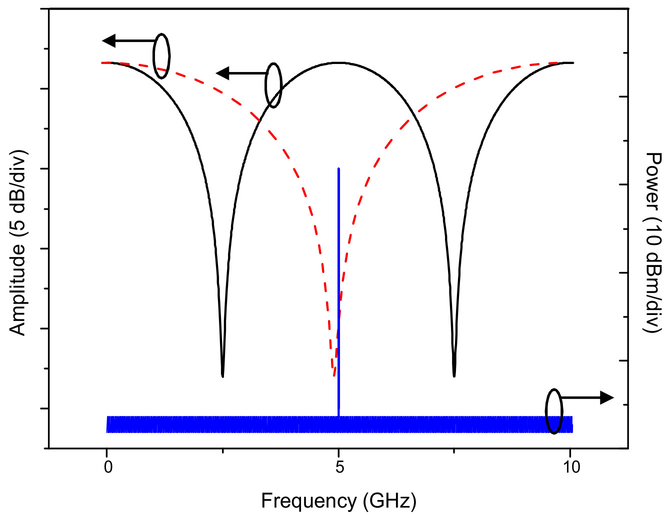

Fig. 2. Frequency response of the double RF modulation based AoA measurement system for the incoming RF signal arrived at the two antennas in different angles (black solid line and red dashed line). System output RF signal spectrum (blue solid line).

radiation pattern. In this case, the AoA can be expressed in term of the phase difference φ_1 and is given by

$$\theta = \sin^{-1}\left(\frac{\varphi_1}{\pi}\right) \tag{3}$$

This shows the AoA can be deduced from the phase difference of the RF signal into the two antennas. The double RF modulation structure shown in Fig. 1 enables this phase difference to be obtained by measuring the output RF signal power.

Fig. 1 shows the CW light from a laser source is modulated by the RF signal received by Antenna 1 and Antenna 2 in MZM1 and MZM2 respectively. Both Mach Zehnder modulators (MZMs) are biased at the quadrature point. They are separated by a distance L. Thus, the CW light is modulated by the same RF signal twice with a time delay depending on the modulator separation and the AoA of the incoming RF signal. The double RF modulated optical signal is detected by a photodetector. Since the CW light is modulated by the same RF signal twice, the structure shown in Fig. 1 has a frequency response with the shape equivalent to that generated by a two-tap delay line based notch filter [12]–[14]. The notch frequency is dependent on the phase difference φ_1 between the RF signal arrived at the two antennas and the phase difference φ_2 introduced by the two modulator separation. The solid line in Fig. 2 shows the frequency response of the AoA measurement system, which is designed so that the passband centre of the frequency response is aligned with the incoming RF signal when the AoA is 0°. When the AoA increases, a notch in the system frequency response moves toward the RF signal as shown by the dashed line in Fig. 2, which reduces the output RF signal power. Hence the system output RF signal power can be used to determine the AoA of the incoming RF signal.

3. Analysis and Simulation Results

Referring to Fig. 1, the MZMs are driven by an RF signal with an angular frequency ω_{RF} arrived at the two antennas having the same length. The optical power into the photodetector can be written as

$$\begin{aligned} P_{out} = \frac{t_{ff1} t_{ff2} P_{in}}{4} \{ & 1 + \cos[\beta_{RF2}\sin(\omega_{RF}t + \varphi_2 - \varphi_1) + \beta_{b2}] + \cos[\beta_{RF1}\sin(\omega_{RF}t) + \beta_{b1}] \\ & + \cos[\beta_{RF1}\sin(\omega_{RF}t) + \beta_{b1}]\cos[\beta_{RF2}\sin(\omega_{RF}t + \varphi_2 - \varphi_1) + \beta_{b2}]\} \end{aligned} \tag{4}$$

where t_{ff1} and t_{ff2} are the insertion loss of MZM1 and MZM2 respectively, P_{in} is the CW light power into MZM1, $\beta_{RF1(2)} = \pi V_{RF1(2)}/V_{\pi 1(2)}$ is the modulation index of MZM1(2), $V_{RF1(2)}$ is the RF signal voltage into MZM1(2), $V_{\pi 1(2)}$ is the switching voltage of MZM1(2), $\beta_{b1(2)}$ is the DC bias of MZM1(2), φ_1 is the phase difference of the incoming RF signal into the two antennas, which is given by (1), and φ_2 is the phase difference introduced by the time difference τ_2 for the CW light undergoes the first and second RF signal modulation when the incoming RF signal arrived at the two antennas at the same time, which is given by

$$\varphi_2 = \omega_{RF}\tau_2 = \frac{\omega_{RF} nL}{c} \tag{5}$$

where n is the fibre refractive index. The MZMs are biased at the quadrature point, i.e., $\beta_{b1} = \beta_{b2} = \pi/2$. The output photocurrent at the input RF signal frequency can be obtained by collecting the terms that contain the RF signal angular frequency ω_{RF} from (4) and is given by

$$I_{RF} = \frac{\Re t_{ff1} t_{ff2} P_{in}}{4}\left[-2J_1\left(\beta_{RF1}\right)\sin\left(\omega_{RF} t\right) - 2J_1\left(\gamma\beta_{RF1}\right)\sin\left(\omega_{RF} t + \varphi_2 - \varphi_1\right)\right] \tag{6}$$

where $\Re$ is the photodetector responsivity, $J_n(x)$ is the Bessel function of nth order of first kind and γ is the ratio of MZM2 and MZM1 modulation index. Assuming the incoming RF signal is a small signal and the antenna separation is $\lambda/2$, the transfer function of the double RF modulation based AoA measurement system can be obtained from (6) and is given by

$$H\left(f_{RF}\right) = \frac{1}{16}\Re^2 t_{ff1}^2 t_{ff2}^2 P_{in}^2 R_{in} R_o \left(\frac{\pi}{V_\pi}\right)^2 \left[\left(\gamma^2 + 1\right) + 2\gamma\cos\left(\frac{nL}{c}\omega_{RF} - \pi\sin\left(\theta\right)\right)\right] \tag{7}$$

where R_{in} is the modulator input resistance and R_o is the photodetector load resistance. Eq. (7) shows the double RF modulation based AoA measurement system has a frequency response with the shape equivalent to a two-tap delay line notch filter frequency response [14]. The notch depth is dependent on the value of γ. The modulator separation L is designed to be λ/n so that the incoming RF signal is located at the centre of the first passband of the system frequency response when the AoA is 0°. This shows the double RF modulation based AoA measurement system requires the knowing of the wavelength or frequency of the incoming RF signal as other AoA measurement techniques [11]. In this case, the output RF signal power can be written as

$$P_{RF,out} = \frac{1}{16}\Re^2 t_{ff1}^2 t_{ff2}^2 P_{in}^2 P_{RF,in} R_{in} R_o \left(\frac{\pi}{V_\pi}\right)^2 \left[\left(\gamma^2 + 1\right) + 2\gamma\cos\left(\pi\sin\left(\theta\right)\right)\right] \tag{8}$$

where $P_{RF,in}$ is the power of the RF signal into MZM1. The relationship between the output RF signal power and the AoA of the RF signal can be seen from (8). The output RF signal power is maximised when the AoA is 0° and is continuously reduced as the AoA increases to 90°. Hence there is no measurement ambiguity even though the frequency response of the double RF modulation based AoA measurement system is periodic. Note that a small modulator separation is needed for measuring the AoA of a high frequency incoming RF signal. This requires the two modulators to be integrated on a photonic integrated circuit or Antenna 2 shown in Fig. 1 to be longer than Antenna 1 to compensate for the effect of the modulator separation. Note that the output RF signal power of the double RF modulation based AoA measurement system is dependent on the system parameters such as the laser power, the modulator insertion loss and the photodiode responsivity. The values of these system parameters can be designed to optimise the system performance. However, the output RF signal power is also dependent on the input RF signal power, which is unknown in practical applications. A calibration process is required to obtain the input RF signal power. This can be done by inserting an optical coupler after MZM1 to couple out part of MZM1 output optical power into a photodetector. The output RF signal power obtained from this photodetector is independent to the RF signal AoA, which can be used to obtain the input RF signal power. Hence the system output RF signal power for 0° AoA, i.e., $P_{RF,out,\theta=0^\circ}$, can be calculated. Therefore the AoA can be obtained

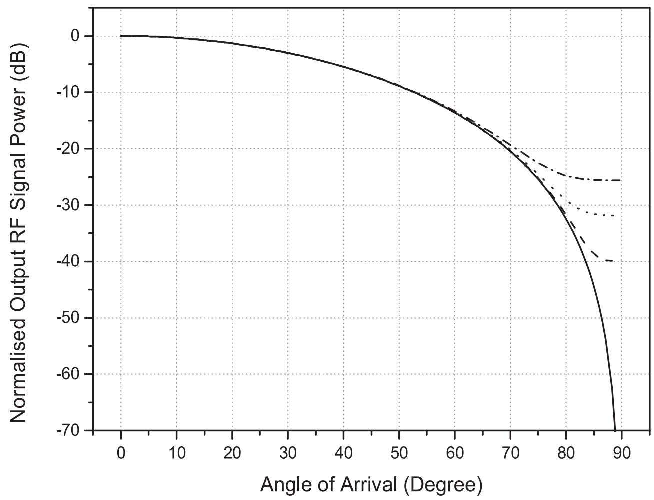

Fig. 3. Normalised output RF signal power versus AoA of the RF signal for MZM2 to MZM1 modulation index ratio γ of 1 (solid line), 0.98 (dashed line), 0.95 (dotted line) and 0.9 (dashed dotted line).

from the normalised output RF signal power, which is defined as

$$P_n = P_{RF,out}/P_{RF,out,\theta=0^\circ} \tag{9}$$

Note that a calibration process is also required in the previously reported AoA measurement system [10] in order to determine the AoA of an incoming RF signal.

The normalised output RF signal power of the proposed structure as a function of the incoming RF signal AoA for different values of γ is shown in Fig. 3. It can be seen that the output RF signal power reduces as the AoA increases. The output RF signal power is very sensitive to the ratio of MZM2 to MZM1 modulation index γ, for an AoA above 80°. In practice, optical modulators have the bias drift problem. This causes fluctuation in the notch depth in the frequency response of the structure shown in Fig. 1. Experimental results show over 30 dB notch depth can be maintained over a period of time without using a modulator bias controller. This indicates that an AoA with less than 1.5° error can be determined from the output RF signal power over the AoA measurement range of 0° to 75°. It should be pointed out that slight fluctuation in the system parameters such as the modulator bias also limits the performance of the systems that use either the sideband power [10] or the optical carrier power [11] to determine the AoA of the RF signal.

In the case where the incoming RF signal has a narrow bandwidth, an electrical power meter can be used after the photodetector to measure the output RF signal power to determine the AoA. In the case of a broadband RF signal, an electrical spectrum analyser can be used after the photodetector to measure the notch frequency in the signal spectrum to determine the AoA, which has been demonstrated in [8]. Therefore the proposed structure is capable of determining the AoA of both narrow and broad band RF signals, which cannot be achieved using the conventional photonics-based AoA measurement techniques [7]–[10]. Note that the double RF modulation based AoA measurement system has a similar structure as that presented in [11]. However, their operation principles are different. The double RF modulation based AoA measurement system uses the output RF signal power to determine the AoA of the incoming RF signal whereas the AoA is determined by the output optical carrier power in [11]. Furthermore, the modulators are biased at different points in the two systems. The advantage of using output RF signal power to determine the AoA of an RF signal is that the system performance is independent to the modulator extinction ratio. Hence high extinction ratio modulators are not required in the proposed structure. The double RF modulation based AoA measurement system also does not require an optical filter. This solves the problems of requiring tight control on the optical source and optical filter wavelengths, and

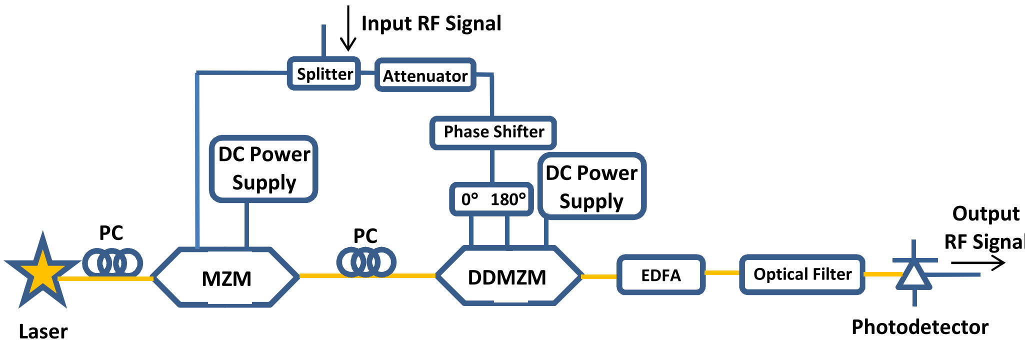

Fig. 4. Experimental setup of the double RF modulation based AoA measurement system.

limiting the incoming RF signal frequency range, presented in the previously reported structures [10], [11]. Most importantly, the structure shown in Fig. 1 can be used to determine the AoA of both narrow and broad band RF signals whereas the structure presented in [11] only applicable for a single-frequency RF signal.

4. Experimental Results

Fig. 4 shows an experimental setup that was used to verify the concept of the proposed AoA measurement technique. The optical source was a wavelength tunable laser. It generated CW light at 1550 nm with 15.6 dBm optical power, which passed through a polarisation controller (PC) into a quadrature-biased MZM (EOSpace AX-OMSS-20). This was followed by another quadrature-biased MZM (Fujitsu FTM7937EZ) via a PC. The first and the second MZM had a switching voltage of 5.4 V and 2.4 V respectively. Note that the second MZM was a dual-drive MZM (DDMZM). Hence a 1–18 GHz bandwidth 180° hybrid coupler was connected to the DDMZM RF ports so that the modulator was functioned as a conventional single-drive MZM. A microwave signal was equally split into two by a 2–26.5 GHz bandwidth power divider. One of the divider outputs was connected to the single-drive MZM. The other output was connected to the DDMZM via an electrical attenuator, an electrical phase shifter and the 180° hybrid coupler. The electrical phase shifter was used to emulate the time delay of the incoming RF signal into Antenna 2 shown in Fig. 1. It provided an adjustable group delay of 0 to 0.2 ns. An erbium-doped fibre amplifier (EDFA) and a 1 nm bandwidth optical filter centred at the laser wavelength were connected to the output of the DDMZM. They were used to compensate for the system loss and to suppress the amplified spontaneous emission noise. They can be avoided by using a high power optical source. The output optical signal was detected by a photodetector (Discovery Semiconductors DSC30S) having a 3 dB bandwidth of 22 GHz.

The frequency response of the double RF modulation based AoA measurement system was measured on a vector network analyser connected to the power splitter input and the photodetector output. Fig. 5(a) shows the system frequency response with a free spectral range (FSR) of 0.76 GHz when the phase shifter was set to the minimum phase shift position. The FSR of the system frequency response is determined by the modulator separation L and the difference of two electrical path lengths between the splitter and the two modulators. The electrical attenuator introduced 5 dB attenuation to the RF signal into the DDMZM so that its modulation index was the same as the MZM modulation index to realise a frequency response with deep notches. The EDFA gain was 14 dB and the output average optical power into the photodetector was 11.7 dBm. Fig. 5(a) also shows the output RF signal spectrum measured on an electrical signal analyser (Keysight N9000A) connected to the photodetector output when a 2.65 GHz RF signal with 5 dBm power was applied to the power splitter. It can be seen that the system has a notch filter shape frequency response and the RF signal is located at the passband centre of the frequency response. The notch frequency

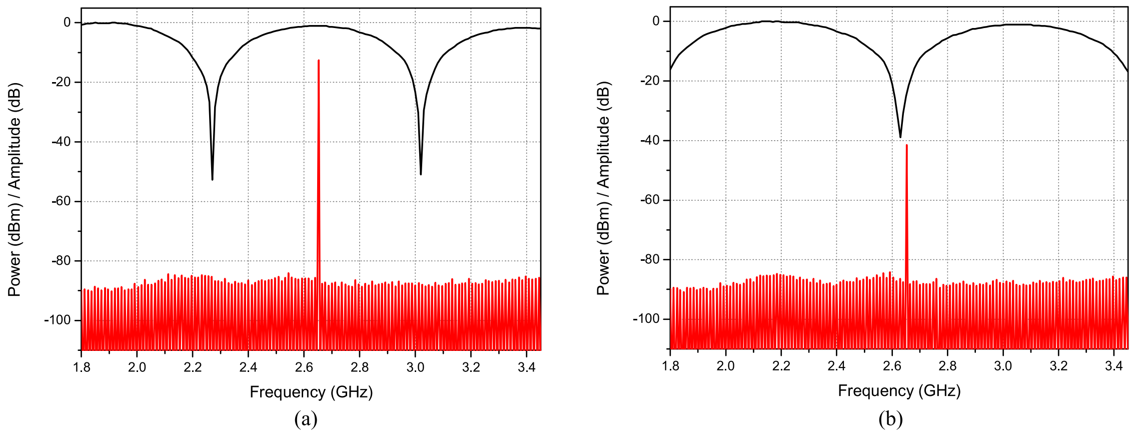

Fig. 5. Measured frequency response and the corresponding output RF signal spectrum when (a) 0 ns and (b) 0.17 ns time delay introduced to the RF signal into the DDMZM.

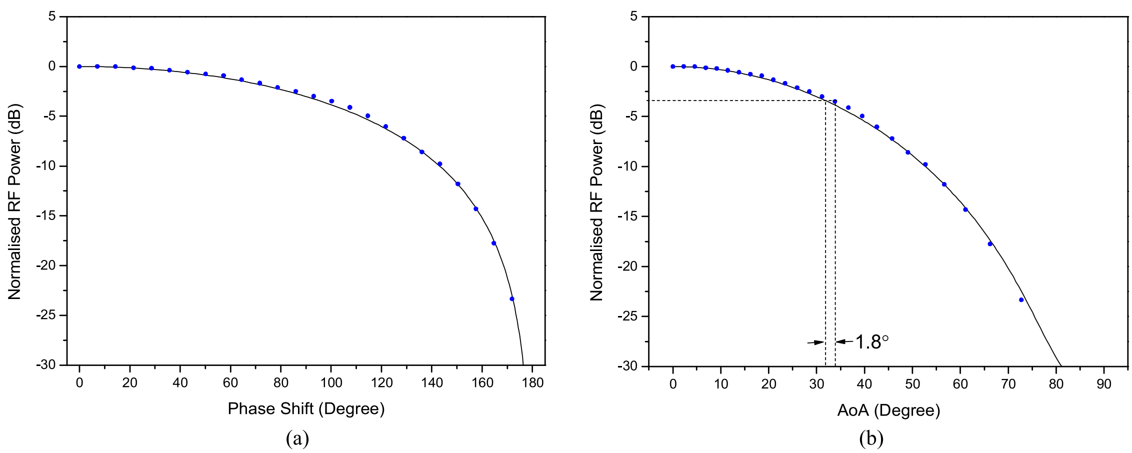

Fig. 6. (a) Experimental measurement (dots) and theoretical prediction (solid) of the relationship between the normalised output RF signal power and the RF signal phase shift for a 2.65 GHz input RF signal. (b) The corresponding measured (dots) and simulated (solid) RF signal AoA.

changed as the electrical phase shifter was tuned to introduce a phase shift or a time delay to the RF signal into the DDMZM. Fig. 5(b) shows the system frequency response with a notch close to the RF signal and the corresponding output RF signal spectrum. Note that the insertion loss of the phase shifter was changed slightly when tuning the phase shift, which reduced the notch depth. The time delay introduced by the phase shifter was measured on the network analyser. Due to the lack of an electrical power meter, the corresponding system output RF signal power was measured using the channel power function on the electrical signal analyser when a 2.65 GHz RF signal was applied to the electrical power splitter. The electrical signal analyser channel bandwidth setting was 1 GHz and the centre frequency was 2.65 GHz, i.e., the input RF signal frequency.

Fig. 6(a) shows the normalised output RF signal powers for different phase shifts. The AoA can be obtained from the phase shift and is shown in Fig. 6(b). It can be seen from the figure that the measurement agrees with the theoretical prediction. To our knowledge, this is the first experimental demonstration of using the output RF signal power of a microwave photonic system to determine the AoA of an incoming RF signal. The same measurement was conducted for an input RF signal at 12.62 GHz, which was located at the centre of the higher order passband of the system frequency response. The output RF signal power was measured for a phase shift ranged

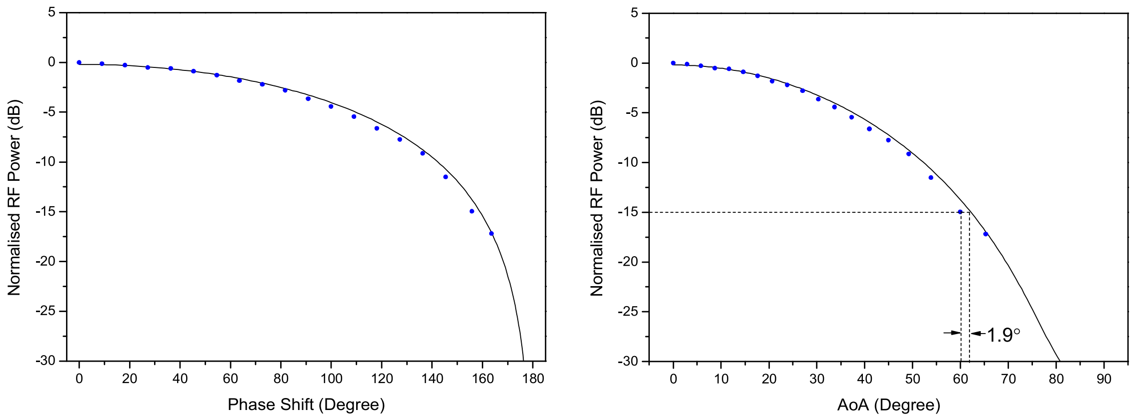

Fig. 7. (a) Experimental measurement (dots) and theoretical prediction (solid) of the relationship between the normalised output RF signal power and the RF signal phase shift for a 12.62 GHz input RF signal. (b) The corresponding measured (dots) and simulated (solid) RF signal AoA.

from 0° to 163.6°, which corresponds to a 0° to 65.3° AoA measurement range, and is shown in Fig. 7(b). This AoA measurement range is significantly larger than that presented in [11]. The experimental results show the AoA measurement error is less than 1.9° for a single frequency RF signal at 2.65 GHz and 12.62 GHz into the system. It should be pointed out that the system frequency response shown in Fig. 5 has the same shape as a negative tap notch filter response [13]. The RF signal frequencies of 2.65 GHz and 12.62 GHz are located at the centre of the fourth and seventeenth passband of the system frequency response respectively. These RF signal frequencies were chosen to demonstrate the AoA measurement system can be operated at different input RF signal frequencies and to simplify the experiment without adjusting the system frequency response FSR. In practice, the modulator separation or the antenna length difference needs to be designed according to the incoming RF signal frequency as was discussed in Section 3.

To verify the proposed structure is applicable for a signal having a band of frequencies, a 20 Mbps PRBS with 15 dBm power generated by an arbitrary waveform generator was upconverted to 2.65 GHz via a 6 GHz bandwidth microwave mixer and was applied to the two MZMs via the power splitter as shown in Fig. 4. The spectrum of the upconverted 20 Mbps PRBS signal is shown in Fig. 8. The output RF signal power after the photodetector was measured using the channel power function on the electrical signal analyser for different RF signal phase shifts. Fig. 9 shows the system output RF signal power reduces as the phase shift increases. It shows a 0°–73.5° AoA measurement range with less than 2.2° error. The error is due to a discrete time delay reading caused by limited network analyser resolution, a slight change in the phase shifter insertion loss while tuning the phase shift and the modulator bias drift. Nevertheless, the results demonstrate the double RF modulation based AoA measurement system can be used to determine the AoA of an RF signal having a single frequency or a band of frequencies. This cannot be done by all previously reported photonics-based AoA measurement techniques. Due to equipment limitation, determining the AoA of a higher bit rate PRBS signal could not be demonstrated. However, it was pointed out in Section 3 that since a high bit rate signal has a broad bandwidth and the time delay of a high bit rate signal received by two antennas generate notches in the signal spectrum, a notch frequency in the signal spectrum can be used to determine the AoA of a high bit rate signal. This technique has been verified using a dual parallel modulator structure [8].

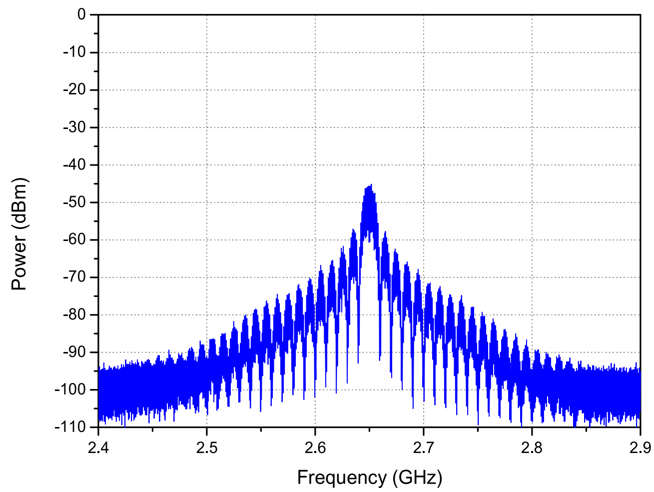

Fig. 8. Spectrum of a 20 Mbps PRBS signal at 2.65 GHz.

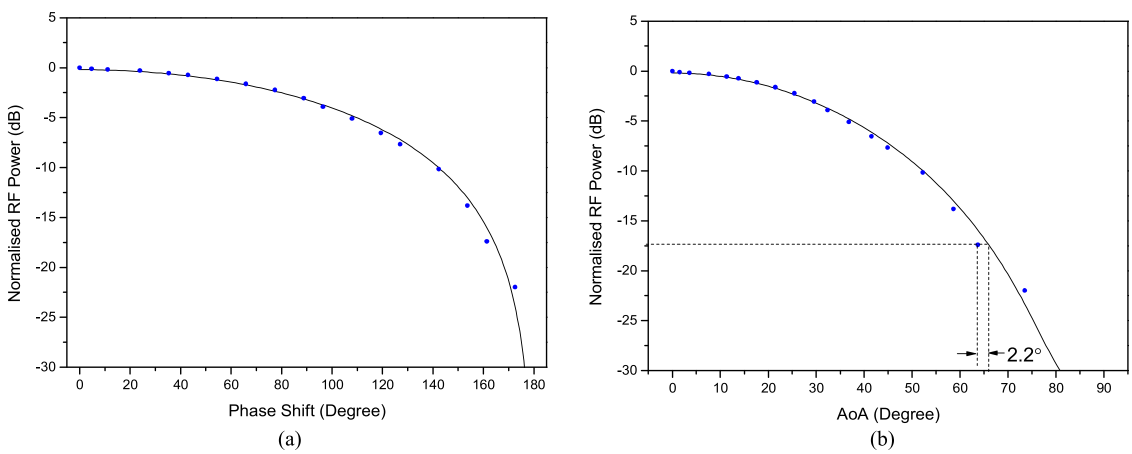

Fig. 9. (a) Experimental measurement (dots) and theoretical prediction (solid) of the relationship between the normalised output RF signal power and the RF signal phase shift for an input 20 Mbps PRBS signal at 2.65 GHz. (b) The corresponding measured (dots) and simulated (solid) RF signal AoA.

5. Conclusion

A new technique for AoA measurement of an RF signal has been presented. It is based on modulating CW light from an optical source twice by an incoming RF signal received by the antennas. The system output RF signal power is dependent on the time delay of the RF signal arrived at the antennas, which in turn dependent on the AoA of the RF signal. The proposed AoA measurement system is capable for measuring the AoA of both narrow and broad band incoming RF signal without requiring high extinction ratio modulators and optical filters. The double RF modulation based AoA measurement system has been analysed and experimentally verified. Experimental results have been presented for the structure that show a wide 0° to over 160° phase shift measurement range, which corresponds to a 0° to over 65° AoA measurement range for the antennas having a half wavelength separation. The AoA measurement error is less than 2.2° for both a single frequency microwave signal and a PRBS signal at a microwave frequency.

References

[1] J. J. Lee *et al.*, "Photonic wideband array antennas," *IEEE Trans. Antennas Propag.*, vol. 43, no. 9, pp. 966–982, Sep. 1995.
[2] R. A. Minasian and K. E. Alameh, "Optical-fiber grating-based beamforming network for microwave phased arrays," *IEEE Trans. Microw. Theory Techn.*, vol. 45, no. 8, pp. 1513–1518, Aug. 1997.
[3] S. Pan and J. Yao, "Photonics-based broadband microwave measurement," *J. Lightw. Technol.*, vol. 35, no. 16, pp. 3498–3513, Aug. 2017.
[4] T. A. Nguyen, E. H. W. Chan, and R. A. Minasian, "Photonic instantaneous multiple frequency measurement using a frequency shifting recirculating delay line structure," *J. Lightw. Technol.*, vol. 32, no. 20, pp. 3831–3838, Oct. 2014.
[5] M. E. Manka, "Microwave photonics for electronic warfare applications," in *Proc. IEEE Int. Top. Meet. Microw. Photon.*, 2008, pp. 275–278.
[6] A. H. Sayed, A. Tarighat, and N. Khajehnouri, "Network-based wireless location: Challenges faced in developing techniques for accurate wireless location information," *IEEE Signal Process. Mag.*, vol. 22, no. 4, pp. 24–40, Jul. 2005.
[7] P. D. Biernacki, A. Ward, L. T. Nichols, and R. D. Esman, "Microwave phase detection for angle of arrival detection using a 4-channel optical downconverter," in *Proc. Int. Top. Meet. Microw. Photon.*, 1998, pp. 137–140.
[8] B. Vidal, M. A. Piqueras, and J. Marti, "Direction-of-arrival estimation of broad microwave signals in phased-array antennas using photonic techniques," *J. Lightw. Technol.*, vol. 24, no. 7, pp. 2741–2745, Jul. 2006.
[9] Z. Tu, A. Wen, Z. Xiu, W. Zhang, and M. Chen, "Angle-of-arrival estimation of broadband microwave signals based on microwave photonic filtering," *IEEE Photon. J.*, vol. 9, no. 5, Oct. 2017, Art. no. 5503208.
[10] Z. Cao, H. P. A. V. D. Boom, R. Lu, Q. Wang, E. Tangdiongga, and A. M. J. Koonen, "Angle-of-arrival measurement of a microwave signal using parallel optical delay detector," *IEEE Photon. Technol. Lett.*, vol. 25, no. 19, pp. 1932–1935, Oct. 2013.
[11] X. Zou, W. Li, W. Pan, B. Luo, L. Yan, and J. Yao, "Photonic approach to the measurement of time-difference-of-arrival and angle-of-arrival of a microwave signal," *Opt. Lett.*, vol. 37, no. 4, pp. 755–757, 2012.
[12] E. H. W. Chan and R. A. Minasian, "Photonic notch filter without optical coherence limitations," *J. Lightw. Technol.*, vol. 22, no. 7, pp. 1811–1817, Jul. 2004.
[13] E. H. W. Chan and R. A. Minasian, "Novel all-optical RF notch filters with equivalent negative tap response," *IEEE Photon. Technol. Lett.*, vol. 16, no. 5, pp. 1370–1372, May 2004.
[14] A. H. Quoc and S. Tedjini, "Experimental investigation on the optical unbalanced Mach-Zehnder interferometers as microwave filters," *IEEE Microw. Guided Wave Lett.*, vol. 4, no. 6, pp. 183–185, Jun. 1994.