Photonic approach to the measurement of time-difference-of-arrival and angle-of-arrival of a microwave signal

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We propose and experimentally demonstrate a photonic approach to the measurement of the time-difference-of-arrival (TDOA) and the angle-of-arrival (AOA) of a microwave signal. In the proposed system, the TDOA and the AOA are equivalently converted into a phase shift between two replicas of a microwave signal received at two cascaded modulators. The light wave from a CW laser is externally modulated by the microwave signal at the first modulator, which is biased to suppress the optical carrier, leading to the generation of two first-order sidebands, which are further modulated by the phase-delayed microwave signal at the second modulator. Two optical components at the carrier wavelength are generated. The total power at the carrier wavelength is a function of the phase shift due to the coherent interference between the two components. Thus, by measuring the optical power, the phase shift is estimated. The AOA is calculated from the measured phase shifts. In our experiment, the phase shift of a microwave signal at 18 GHz from −160° to 40° is measured with measurement errors of less than ±2.5°.

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The ability to measure the instantaneous frequency, pulse width, angle-of-arrival (AOA), and modulation format of a microwave signal is of great importance for electronic warfare and radar applications [1]. One critical challenge for the implementation of the measurement is the requirement for a large instantaneous bandwidth, usually from 2 to 100 GHz or wider [1], which is difficult to fulfill using state-of-the-art electronic solutions.

Photonics has the intrinsic feature of wide instantaneous bandwidth, which is suitable for the generation, transmission, control, and processing of wideband microwave signals [2–6]. In addition, its immunity to electromagnetic interference makes photonics a solution particularly suitable for defense applications. In the field of microwave measurement, a number of photonic approaches for frequency estimation [7–15] and spectrum analysis [16–18] have been proposed, but few approaches deal with the measurement of critical parameters such as the AOA [19,20] and the time-difference-of-arrival (TDOA).

In this Letter, we propose a photonic approach to the measurement of the TDOA and the AOA of a microwave signal. In the proposed system, two electro-optic modulators (EOMs) that are both biased at the minimum transmission point to suppress the optical carrier are employed. If two replicas of a microwave signal with a given phase shift are received by the two EOMs, at the output of the second EOM, two optical components at the carrier wavelength are generated where the total power is a function of the phase shift. By simply measuring the optical power, the phase shift can be estimated. The TDOA and the AOA are then calculated based on the measured phase shift. The proposed approach has the advantages of all-optical processing and stable interference, making the system compact with high accuracy.

The proposed approach is schematically shown in Fig. 1. The system consists of a CW laser, two EOMs (EOM-I and EOM-II), an optical filter, and a power meter. EOM-I and EOM-II are connected in series such that a phase shift (i.e., ϕ) between two replicas of a microwave signal, received at the two modulators, would result. The two modulators are both biased to suppress the optical carrier. The light wave of the CW laser is first modulated by the microwave signal received at EOM-I. Because the carrier is suppressed, only two first-order sidebands are generated. The two sidebands are then modulated by the phase-delayed microwave signal received at EOM-II. Again, EOM-II is also biased to suppress the carrier; consequently, two optical components with an identical frequency at the carrier wavelength will be generated. Because of the phase difference between the two components, the total power at the carrier wavelength will

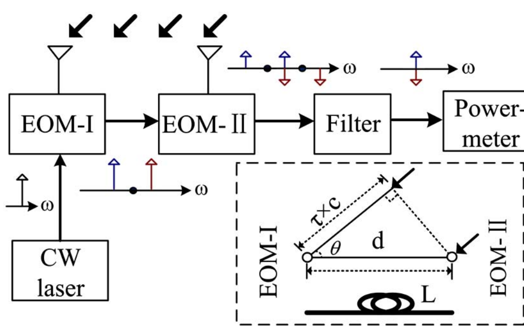

Fig. 1. (Color online) Schematic diagram of the proposed approach. Inset, illustration of the TDOA and AOA.

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be a function of the phase shift. Thus, by detecting the power at the carrier wavelength, the phase shift can be estimated, leading to the measurement of the TDOA and the AOA.

Assuming that the AOA is θ, the TDOA is then given by $\tau = d\cos\theta/c$, where d is the distance between the two receiving antennas at the two modulators and c is the light velocity in vacuum, as shown in the inset of Fig. 1. Then, two equations that relate the TDOA, the AOA, and the phase shift, ϕ, are given by

$$-\Omega\tau + \Omega L/c = \phi + 2k\pi, \qquad \theta = \cos^{-1}(\tau c/d), \tag{1}$$

where Ω is the angular frequency of the microwave signal, L is the length of the optical link between the two modulators, and k is an integer that can be determined from the physical parameters of the proposed system.

Because EOM-I is biased to eliminate the carrier, at the output of EOM-I the optical field can be written as

$$E_1(t) \propto jJ_1(\beta_1)[\exp j(\omega-\Omega)t + \exp j(\omega+\Omega)t)], \tag{2}$$

where ω is the angular frequency of the light wave from the CW laser, β_1 is the modulation index of EOM-I, and $J_1(\cdot)$ is the first-order Bessel function of the first kind. As can be seen, two sidebands are generated.

The two sidebands in Eq. (2) are then modulated by a phase-delayed replica of the microwave signal. Because EOM-II is also biased at the minimum transmission point, the field at the output of EOM-II is written as

$$\begin{aligned} E_2(t) &\propto \frac{j}{2}J_1(\beta_1)\times\left\{\begin{array}{l}\exp j[(\omega-\Omega)t+\beta_2\cos(\Omega t+\phi)]+\\ \exp j[(\omega-\Omega)t-\beta_2\cos(\Omega t+\phi)]+\\ \exp j[(\omega+\Omega)t+\beta_2\cos(\Omega t+\phi)]+\\ \exp j[(\omega+\Omega)t-\beta_2\cos(\Omega t+\phi)]\end{array}\right\} \\ &= -J_1(\beta_1)J_1(\beta_2)\left\{\begin{array}{c}\exp j[(\omega-2\Omega)t-\phi)]+\\ \exp j[(\omega+2\Omega)t+\phi)]+\\ \exp j(\omega t-\phi)+\exp j(\omega t+\phi)\end{array}\right\}, \end{aligned} \tag{3}$$

where β_2 is the modulation index of EOM-II. As can be seen, two optical components with an identical frequency of ω are generated. Other frequency components are also generated, which can be removed using an optical filter with a fixed central wavelength and passband. The total optical power of the two components is given by

$$P_3 \propto 2[J_1(\beta_1)J_1(\beta_2)]^2 \times [1+\cos(2\phi)]. \tag{4}$$

It is clear that the optical power is a function of the phase shift. Therefore, by measuring the optical power, the phase shift can be estimated. From the estimated phase shift, the TDOA and the AOA can be calculated based on Eq. (1). Note that a stable carrier suppression at the two modulators is critical for the AOA estimation, which can be achieved via bias control or a notch filter.

To verify the proposed approach, an experiment is performed. As shown in Fig. 2, the first EOM is implemented by using a Mach–Zehnder modulator (MZM). Because of the high sensitivity of the MZM to the bias drift and the lack of a bias controller, the optical carrier is removed in the experiment by using a fiber Bragg grating (FBG) serving as a notch filter, rather than a biased MZM, to ensure a stable operation for carrier suppression. As illustrated in Fig. 3, the transmission spectrum of the FBG shows a deep notch of over 45 dB, which leads to a complete suppression of the optical carrier and such that only two sidebands are obtained at the output of the FBG.

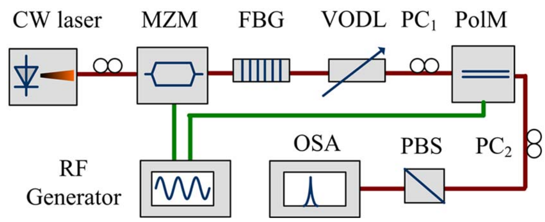

Fig. 2. (Color online) Experimental setup: MZM, Mach–Zehnder modulator; FBG, fiber Bragg grating; VODL, variable optical delay line; PC, polarization controller; PolM, polarization modulator; PBS, polarization beam splitter; OSA, optical spectrum analyzer.

The second EOM is implemented using a polarization modulator (PolM) in combination with a polarization beam splitter (PBS). It has been demonstrated that a PolM, in combination with a PBS, can operate as an MZM that is biased at the minimum transmission point by properly controlling the polarization direction of the incident light relative to the principal axis of the PolM and the principal axis of the PBS [21]. The two sidebands shown in Fig. 3(b) are then sent to the PolM-based MZM. At the output of the PolM-based MZM, two optical components at the carrier wavelength with their power being a function of the phase shift are generated.

In the experiment, to emulate the change of the TDOA and the AOA, a phase shift between two replicas of a microwave signal at 18 GHz is applied to the MZM and the PolM. The phase shift is tuned at a step of 20° from −160° to 40° using a manually variable optical delay line (VODL). The optical power that has a fixed relationship with the phase shift is measured by using an optical spectrum analyzer.

The measured powers corresponding to different phase shifts are shown in Fig. 4 as circles. The theoretical power distribution as a function of the phase shift is also shown (dotted curve). A good agreement is reached. The measured phase shifts and the measurement errors are shown in Fig. 5. It is clearly seen that the measurement errors are less than ±2.5° within the range from −160° to 40°.

Based on Eq. (1), the TDOA and the AOA can then be calculated from the estimated phase shifts. Here, $d = 0.1$ m and $L = 3.67$ m. For the TDOA, an effective measurement range from −24.7 to 6.2 ps can be obtained from

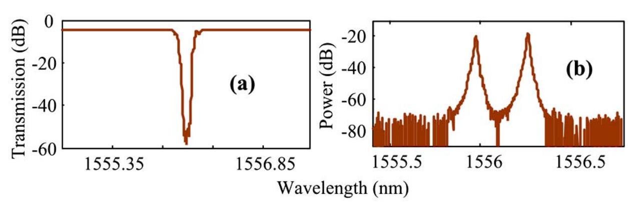

Fig. 3. (Color online) (a) Transmission spectrum of the FBG and (b) the spectrum detected at the output of the FBG.

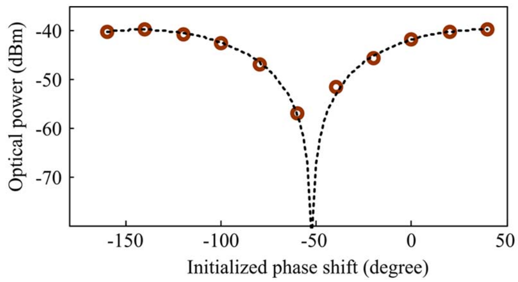

Fig. 4. (Color online) Experimental results (circles) and theoretical trend (dotted curve) for the total optical power.

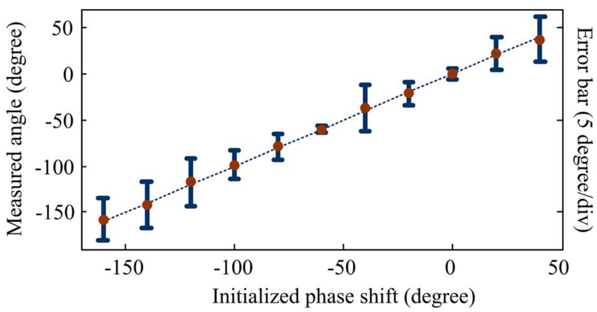

Fig. 5. (Color online) Measured phase shifts (circle dots) and the corresponding measurement errors (vertical bars).

the estimated phase shifts, when the constant time delay induced by the photonic link is excluded. The measurement errors for the TDOA are less than ± 0.38 ps. The AOA can be derived from the values of the TDOA, which ranges from 88.93° to 94.25°. The measurement errors for the AOA are less than $\pm 0.07°$. The above measurement range of the AOA could be increased by reducing d. For example, if $d = 4.2$ mm, the measurement range of the AOA can be as large as 180° and the ambiguity between θ and $\theta + 90^{\circ}$ can be discriminated due to the opposite sign of the cosine term.

To improve the measurement accuracy, we have to reduce the measurement error for ϕ, which can be done by performing the phase-to-intensity mapping in the linear range of the cosine function but results in a reduced measurement range. To keep a large measurement range, multiple units, each of which is responsible for a smaller range, may be employed. In addition, the integration of the two modulators on a single chip would also improve the measurement accuracy, because the perturbations in the optical length between the two modulators induced by environmental influences can be compensated.

Here the AOA is measured assuming the frequency is known. For practical applications, the frequency is not known, so the proposed approach may be combined with photonic frequency measurement technique to perform both frequency measurement and AOA estimation.

In conclusion, a photonic approach to the measurement of the TDOA and the AOA of a microwave signal was proposed and experimentally demonstrated. The key contribution of this work was the measurement of the phase shift between two replicas of a microwave signal through the measurement of the optical power of two optical components that were generated by using two MZMs that were biased at the minimum transmission point. The TDOA and the AOA were then calculated from the measured phase shifts. In our experiment, a phase shift from −160° to 40° between two replicas of a microwave signal at 18 GHz was measured with measurement errors less than ±2.5°. An AOA from 88.93° to 94.25° was thus calculated from the measured phase shift.

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