Photonic approach to the simultaneous measurement of the frequency, amplitude, pulse width, and time of arrival of a microwave signal

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A photonic approach to the simultaneous measurement of the frequency, pulse amplitude (PA), pulse width (PW), and time of arrival (TOA) of an unknown pulsed microwave signal is proposed and demonstrated. The measurement is performed based on optical carrier-suppressed modulation, complementary optical filtering, low-speed photodetection, and electrical signal processing. A proof-of-concept experiment is carried out. A frequency measurement range of 2–11 GHz with a measurement error for frequency, PA, PW, and TOA within ±0.1 GHz, ±0.05 V, ±1 ns, and ±0.16 ns is achieved.

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In the field of electronic warfare (EW), it is of critical importance to analyze an intercepted radio-frequency (RF) signal from a hostile radar or communication system. In order to effectively jam an enemy receiver and sort out the pulse trains of various radars, the frequency of the signal from the enemy transmitter must be accurately and quickly determined [1]. The electrical approaches can achieve high measurement resolution and large dynamic range, but the frequency measurement range is limited due to the electronic bottleneck. The electrical solutions also suffer from other limitations such as high power consumption, vulnerability to electromagnetic interference (EMI), and bulky size. To overcome these limitations, photonic-assisted instantaneous frequency measurement was proposed and considered a promising solution because of the advantageous features such as near real-time measurement, large measurement range, low loss, and small size [2–12].

In addition to the frequency information, it is also essential to acquire other parameters of a microwave signal. For example, in a radar system, the emitted signal is usually in the form of a pulse train. Three other important parameters including the pulse amplitude (PA), pulse width (PW), and time of arrival (TOA) are also important for EW applications [1]. Typically, an accurate PA information can be used for the estimation of the distance of a radar, or for inverse gain jamming; the PW can be used to coarsely identify the type of radars (e.g., the pulses generated by the weapon radars always have a short PW); and the TOA provides the information of the pulse repetition rate, which can also be used to predict the TOA of the next pulse for a jammer. Therefore, it would be of great interest to develop photonic approaches that can simultaneously identify the frequency as well as the PA, PW, TOA of a pulsed microwave signal.

In this Letter, we propose and demonstrate, for the first time to the best of our knowledge, a photonic system that can simultaneously measure the frequency, PA, PW, and TOA of an unknown pulsed microwave signal. The operation is mathematically analyzed, which is then verified by a proof-of-concept experiment. A frequency measurement range of 2–11 GHz with a measurement error for frequency, PA, PW, and TOA within ±0.1 GHz, ±0.05 V, ±1 ns, and ±0.16 ns is achieved.

Figure 1 shows the schematic of the proposed photonic microwave measurement system. An optical carrier from a laser diode (LD) is sent to a Mach–Zehnder modulator (MZM) through a polarization controller (PC). The MZM is biased at the minimum transmission point. A pair of complementary optical filters with a sinusoidal spectral response are placed at the output of the MZM. The complementary optical filters are implemented using a polarization-maintaining fiber (PMF) which functions as an asymmetric Mach–Zehnder interferometer (AMZI) with dual outputs [4]. The filtered optical signals are sent to two photodetectors (PDs) for optical-to-electrical conversion. The resulted electrical signals are processed by two analog-to-digital convertors (ADCs) and an electrical signal processing module.

Mathematically, when a pulsed microwave signal $u(t) = V_e R(t) \cdot \cos(\omega_e t)$ is introduced to the MZM, where ω_e is the angular frequency, V_e is the amplitude, and $R(t)$

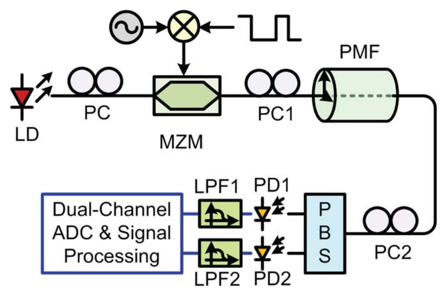

Fig. 1. (Color online) Schematic of the proposed photonic-assisted microwave measurement system. LD: laser diode; PC: polarization controller; MZM: Mach-Zehnder modulator; PMF: polarization-maintaining fiber; PBS: polarization beam splitter. PD: photodetector; LPF: low-pass filter.

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is the normalized pulse profile, the optical field at the output of the MZM can be written as

$$E(t) = \sqrt{P_0} \exp(j\omega_c t) \sin[\beta_1 R(t) \cos \omega_e t], \quad (1)$$

where P_0 and ω_c are, respectively, the optical power and the angular frequency of the optical carrier, $\beta_1 = \pi V_e/V_\pi$ is the modulation depth, and V_π is the half-wave voltage of the MZM.

For small-signal modulation ($\beta_1 < \pi/6$), which is the condition to avoid signal distortion in the MZM, Eq. (1) can be rewritten as

$$E(t) \approx \frac{\beta_1 \sqrt{P_0}}{2} R(t) \exp(j\omega_c t)[\exp(j\omega_e t) + \exp(-j\omega_e t)]. \quad (2)$$

For most narrow-band radars or radio communication systems, $R(t)$ has a bandwidth much smaller than the carrier frequency. Therefore, Eq. (2) can be seen as a dual-wavelength signal with angular frequencies of $\omega_c \pm \omega_e$ in the frequency domain. When the optical filter pair is adjusted with the transmission responses given by

$$T_\pm(\omega) \propto 1 \pm \gamma \cos\left(\frac{\omega - \omega_c}{\mathrm{FSR}}\right), \quad (3)$$

where FSR is the free spectral range of the sinusoidal filters and γ is the relative peak-to-notch contrast ratio, the two wavelengths would undergo the same optical losses. By square-law detection, the filtered optical signals at the outputs of the PDs are given by

$$I_\pm = \frac{\eta_\pm}{2} \beta_1^2 R^2(t) \left[1 \pm \gamma \cos\left(\frac{\omega_e}{\mathrm{FSR}}\right)\right] [1 + \cos 2\omega_e t], \quad (4)$$

where $\pm$ represents the upper and lower paths, $\eta_\pm$ is a parameter related to the insertion loss of each optical path and the responsivity of each PD. The PDs are selected to have a 3 dB cutoff frequency larger than the bandwidth of $R(t)$ but much smaller than $2\omega_e$, so the $2\omega_e$ term in the right-hand side of Eq. (4) can be neglected. Based on Eq. (4), we obtain an amplitude comparison function (ACF) between the two output currents

$$\mathrm{ACF} = \frac{I_-}{I_+} = \frac{\eta_-}{\eta_+} \frac{1 - \gamma \cos\left(\frac{\omega_e}{\mathrm{FSR}}\right)}{1 + \gamma \cos\left(\frac{\omega_e}{\mathrm{FSR}}\right)}. \quad (5)$$

The values of η_+ and η_- can be obtained by introducing a test microwave signal with a known frequency and amplitude to the MZM. Since the ACF is monotonically increasing with ω_e over a frequency band from DC to 1/2FSR, ω_e can be estimated based on the value of the ACF by the following expression,

$$\omega_e = \mathrm{FSR} \cdot \cos^{-1}\left(\frac{1}{\gamma} \frac{1 - \frac{\eta_+}{\eta_-}\mathrm{ACF}}{1 + \frac{\eta_+}{\eta_-}\mathrm{ACF}}\right). \quad (6)$$

Knowing ω_e, other information of the pulsed microwave signal can also be achieved. Based on Eq. (4) we have

$$V_e R(t) = \sqrt{\frac{2V_\pi^2 I_\pm}{\pi^2 \eta_\pm \left[1 \pm \cos\left(\frac{\omega_e}{\mathrm{FSR}}\right)\right]}}. \quad (7)$$

The signals in Eq. (7) can be digitized using two ADCs and then analyzed using a digital signal processor. For instance, V_e can be obtained by finding the maximum value of $V_e R(t)$. The PW and TOA can also be measured based on Eq. (7). The bandwidth of the ADCs and digital signal processor can be as small as the bandwidth of $R(t)$. Therefore, the system can be implemented by low-frequency components at a low cost.

A proof-of-concept experiment based on the setup shown in Fig. 1 is carried out. A light wave at 1555.75 nm emitted from a LD is intensity modulated at a 40 GHz MZM by a pulsed microwave signal. The pulsed microwave signal is generated by mixing a CW microwave signal from a microwave source (Agilent E8267D) with a NRZ signal (Anritsu MP1763C) at an electrical mixer ($2 \sim 18$ GHz). The MZM is biased at the minimum transmission point to perform carrier-suppressed modulation. A PMF-based AMZI is used to form a pair of complementary optical filters with a sinusoidal spectral response. The differential group delay (DGD) of the PMF is 38.8 ps, so the FSR of the filters is 25.8 GHz. The PDs are paired and have a 3 dB bandwidth of 40 GHz and a responsivity of 0.65 A/W. A low-pass filter with a cutoff frequency of 625 MHz is connected to each PD, to eliminate the high frequency component in the detected signal. A dual-channel digital oscilloscope is used to serve as the ADCs and the digital signal processor.

Figure 2 shows the optical spectrum and waveform of the carrier-suppressed optical signal at the output of the MZM. The center frequency of the pulsed microwave signal is 10 GHz, the data rate of the signal is 160 Mb/s, the fixed pattern is 0011010011101100, and the peak-to-peak voltage (Vpp) is 2 V. Figure 3(a) shows the transmission response of the complementary filters. The extinction ratio of the filters is 18.8 dB, corresponding to a γ of 0.974. The wavelength of the optical carrier is located at the spectral peak of one filter and the spectral valley of the other filter. The optical spectra of the two filtered signals are shown in Fig. 3(b). The peak power in one channel is 9.115 dB less than that in the other channel. Figure 3(c) shows the waveforms of the detected signals after the PDs observed by the digital oscilloscope. The pulsed microwave signal is downconverted to the baseband. The pulse pattern and pulse width are the same as

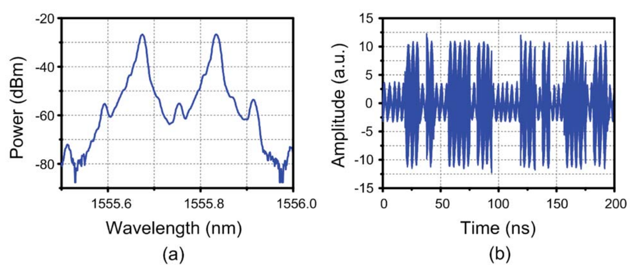

Fig. 2. (Color online) Optical spectrum and waveform of the optical signal modulated by a 10 GHz pulsed microwave signal when the MZM is biased at the minimum transmission point.

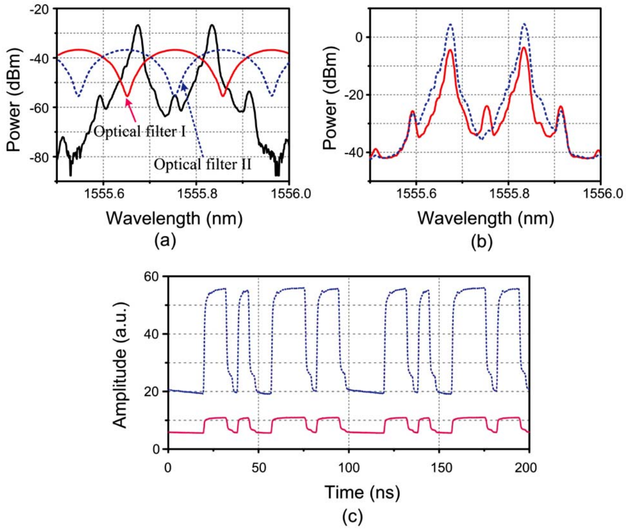

Fig. 3. (Color online) (a) Transmission responses of the complementary filters; (b) the optical spectra of the filtered optical signal; (c) the waveforms of the signals after photodetection.

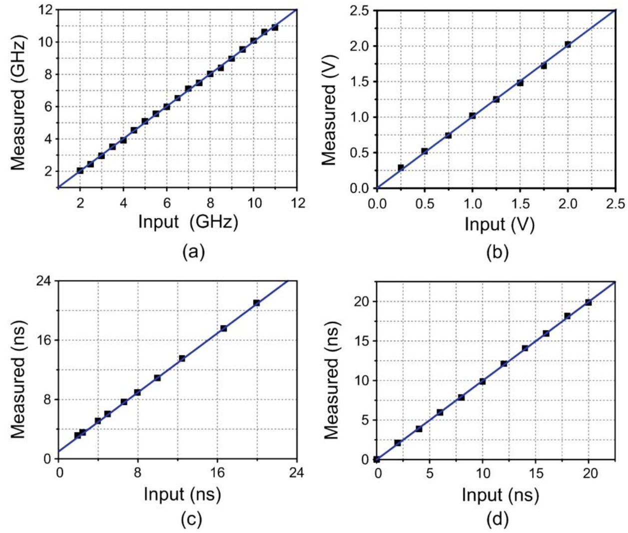

Fig. 4. (Color online) The estimated (a) frequency, (b) PA, (c) PW, and (d) TOA of the pulsed microwave signal versus the actual values based on the proposed method.

those of the input pulsed microwave signal. For instance, the PW of the first pulse in Fig. 3(c) is 13.49 ns, very close to the actual PW (12.45 ns) of the input pulsed microwave signal. It should be noted that the ~1 ns error is due to the low-pass filtering after the PDs, which broadens the pulse. Therefore, both the PW and TOA can be obtained from Fig. 3(c). In addition, based on the two peak-to-peak voltages, we obtain that $\eta_-/\eta_+ = 0.895$ and $\eta_- = 0.026$ based on Eq. (4) and Eq. (5).

Using the parameters obtained above, we can then measure the center frequency, PA, PW, and TOA of an unknown pulsed microwave signal. Figure 4 shows the measurement results versus the actual results based on the proposed method. When the center frequency varied from 2 GHz to 11 GHz, the measurement error is limited within ±0.1 GHz. The error of the PA measurement is less than ±0.05 V within a range of 0.25–2 V (Vpp). The measurement of the PW has a fixed error around 1 ns because of the low-pass filtering effect. When the pulsed microwave signal is delayed by 0–20 ns, we can observe the similar time shift in the oscilloscope. The measurement error is less than ±0.16 ns. It should be noted that, although we only validate the measurement of a NRZ signal in this work, the method is effective to the measurement of signals with different modulation formats because there is no mathematical restriction on $R(t)$ in (Eq. 7).

In conclusion, we have proposed and demonstrated a photonic approach to simultaneously measuring the frequency, PA, PW, and TOA of a pulsed microwave signal. In the proof-of-concept experiment, a measurement of the frequency, PA, PW, and TOA was successfully performed when the frequency or amplitude of the pulsed microwave signal was varied from 2 GHz to 11 GHz or from 0.25 V to 2 V. A good agreement between the measured and the actual values was achieved. The approach provides an important solution for the measurement of an unknown pulsed microwave signal which can find applications in electronic warfare systems.

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