Instantaneous Microwave Frequency Measurement Using a Photonic Microwave Filter Pair

Shilong Pan, *Member, IEEE*, and Jianping Yao, *Senior Member, IEEE*

***Abstract*—Photonics-assisted instantaneous microwave frequency measurement (IFM) has been a topic of interest recently. To perform IFM, an amplitude comparison function (ACF) that relates the microwave frequency to the microwave powers by which the microwave frequency can be estimated by measuring the microwave powers should be established. In this letter, a two-tap photonic microwave filter pair with complementary frequency responses is employed for achieving IFM. Thanks to the complementary nature of the transfer functions of the filter pair, a quasi-linear monotonically decreasing ACF over a large frequency band is obtained, which ensures an improved measurement range and accuracy. An experiment is performed. A microwave frequency measurement range as large as 36 GHz with a measurement accuracy better than ±0.2 GHz is experimentally demonstrated.**

***Index Terms*—Electronic warfare, instantaneous microwave frequency measurement (IMF), microwave photonics, optical microwave signal processing, polarization modulator.**

I. Introduction

In the field of electronic warfare, it is important to analyze intercepted radio frequency (RF) signals from radars and communications systems. Typically, the frequency of a radar or communication system can be varied from hundreds of megaHertz to hundreds of gigaHertz. A microwave receiver, however, usually operates in a very narrow frequency band. For a broadband system, an instantaneous frequency measurement (IFM) module is thus required to instantaneously identify the carrier frequency of an unknown RF signal before passing it to a specialized receiver for further processing [1]. Thanks to the advantageous features such as near real-time measurement, large measurement range, low loss, and small size, photonics-assisted IFM is considered a promising solution.

Several photonics methods have been proposed for microwave frequency measurement. For example, a microwave frequency can be measured using an optical channelizer [2], but the implementation requires the use of a specially designed diffraction grating and a photodetector (PD) array, making the system bulky and costly. In addition, the measurement range is usually limited (<20 GHz) and the measurement accuracy is also low (>1 GHz). The frequency of a microwave signal can also be measured based on frequency-to-time mapping [3]. The advantage of the approach is that different frequency components in the signal can be simultaneously measured. The major limitations of the technique are the poor measurement accuracy and high cost. Recently, techniques to measure the frequency of a microwave signal based on frequency-to-power mapping have been demonstrated [3]–[14]. By passing the microwave signal that is carried by two optical carriers through a dispersive device, a unique relationship between the optical or microwave power ratio and the microwave frequency is established due to the different power penalty functions. The microwave frequency is simply estimated by measuring the optical [3]–[7] or microwave powers [8]–[14]. The key advantage of the approaches in [3]–[14] is that IFM with a large frequency measurement range (>20 GHz) and a high measurement accuracy (<200 MHz) is achievable.

In this letter, a novel technique to implement IFM based on a simple microwave photonic system consisting of a two-tap photonic microwave filter pair with complementary frequency responses is proposed and experimentally demonstrated. The photonic microwave filter pair, one is a low-pass filter and the other is a bandpass filter, is achieved using a polarization modulator (PolM) and two sections of polarization maintaining fiber (PMF). Thanks to the complementary nature of the frequency responses of the photonic microwave filter pair, we obtain an amplitude comparison function (ACF), a ratio between the two transfer functions of the filter pair, which is quasi-linear and monotonically decreasing over a large frequency band. The measurement of the microwave frequency can be done by simply measuring the microwave powers from the two outputs of the photonic microwave filter pair. The accuracy of measurement is independent of the laser wavelength, which would eliminate the requirement for a highly wavelength-stable laser source, and hence, significantly decrease the cost and complexity of the entire system. An experiment is performed. A microwave frequency measurement range as large as 36 GHz with a measurement accuracy better than ±0.2 GHz is experimentally demonstrated.

II. Principle

Photonic microwave filters are usually implemented based on a delay-line structure, in which a microwave signal is modulated on one or multiple optical carriers at an optical modulator; the modulated light waves are then sent to a time-delay device to introduce different time delays; the time delayed microwave signals are then recovered and summed at a PD [15]. There are two parameters that uniquely determine the frequency response of a photonic microwave filter: the time delay difference and the tap coefficients. The time delay difference determines the free spectral range (FSR) and the tap coefficients determine the shape of

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The authors are with the Microwave Photonics Research Laboratory, School of Information Technology and Engineering, University of Ottawa, Ottawa, ON K1N 6N5 Canada (e-mail: jpyao@site.uOttawa.ca).

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the frequency response. Mathematically, the frequency response of an N-tap microwave delay-line filter is given by [15]

$$H(f) = \sum_{n=0}^{N-1} a_k e^{-j2k\pi f\tau} \tag{1}$$

where τ is the time delay difference and a_n is the tap coefficient. For a two-tap filter with coefficients of (1, 1) or (1, -1), the power frequency response is given by

$$\left|H_{(1,1)}(f)\right|^2 = 2\cos^2(\pi f\tau) \tag{2}$$

or

$$\left|H_{(1,-1)}(f)\right|^2 = 2\sin^2(\pi f\tau). \tag{3}$$

As can be seen from (2) and (3), the two power frequency responses are complementary, corresponding to a low-pass and a bandpass filter. The ratio between the two power spectral responses, which is referred to as the ACF, is given by

$$\text{ACF} = \frac{\left|H_{(1,1)}(f)\right|^2}{\left|H_{(1,-1)}(f)\right|^2} = \frac{1}{\tan^2(\pi f\tau)}. \tag{4}$$

From (4), the ACF is monotonically decreasing over a frequency band from dc to $1/2\tau$. Therefore, based on the value of the ACF, we can estimate the frequency of the input microwave signal by the following expression:

$$f = \frac{1}{\pi\tau\tan^{-1}\sqrt{\text{ACF}}}. \tag{5}$$

The maximum measurement range is determined by τ. To have a larger measurement range, we may design the filter pair to have a greater FSR. Since the photonic microwave filter pair is implemented in the incoherent regime using an incoherent source [15], the IFM scheme would have a low requirement for the quality of the laser source. The system would also have improved system stability because the poor stability of the laser source would not affect the performance of the filter pair due to the incoherent operation of the filter pair. This feature is highly desirable in defense systems.

If the photonic microwave filter pair is implemented using two independent sets of light sources, modulators and PDs, the independent variations of the laser output powers, the optical path losses, the phase modulation indices, and the responsivities of the PDs would be transferred to the ACF, leading to poor measurement accuracy. For IFM, however, we expect that the ACF is independent of these variations. If the photonic microwave filter pair is implemented using a single laser source and a single modulator, the variations transferred to the ACF would be completely cancelled out. In addition, the difference of the responsivities of the PDs can be compensated by adjusting the path losses.

Fig. 1 shows the photonic microwave filter pair that is implemented using a single laser source and a single modulator. The key component in the filter pair is the modulator which is a polarization modulator (PolM). A PolM is a special phase modulator that supports both TE and TM modes, with complementary phase modulation indexes. A linearly polarized CW light wave from a laser diode (LD) is fiber coupled to the PolM with its polarization direction oriented at an angle of 45° to one principal axis of the PolM by a polarization controller (PC). The microwave signal with its frequency to be measured is applied to

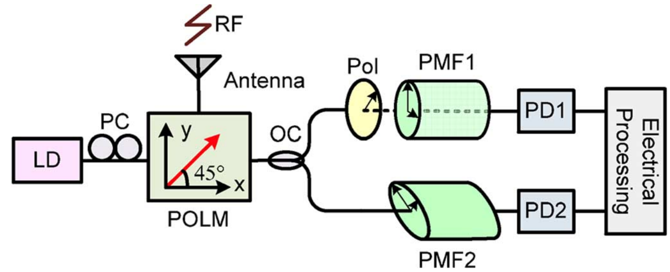

Fig. 1. Schematic of the proposed microwave frequency measurement system. Pol: polarizer.

the PolM via its RF port. The incident light waves would experience complementary phase modulations along the two principal axes (x and y). The signal at the output of the PolM is then split into two channels by a polarization maintaining optical coupler (OC). In the upper channel, an optical polarizer with its transmission axis oriented at an angle of 45° to one principal axis of the PolM is incorporated to convert the phase-modulated signal to an intensity-modulated signal. A section of PMF (PMF1) with its fast axis aligned to one principal axis of the PolM is connected after the polarizer. The intensity-modulated signal after the polarizer is thus split equally along the fast and slow axes of PMF1. Due to the differential group delay (DGD) of the PMF, a time delay difference determined by the birefringence and the length of the PMF is produced between the two signals along the two principal axes. The time-delayed signals are then detected by a PD. The entire operation corresponds to a two-tap photonic microwave delay-line filter with two coefficients of (1, 1). In the lower channel, the phase-modulated signals are directly sent to a second section of PMF (PMF2) with its fast axis oriented at an angle of 45° to one principal axis of the PolM. The phase-modulated signals are then converted to two complementary intensity-modulated signals along the fast and slow axes. After undergoing a time delay difference in PMF2, the two signals are detected at a second PD. Due to the complementary nature of the two time delayed signals, a two-tap photonic microwave filter with coefficients of (1, -1) is implemented [15].

III. Measurement Results and Discussion

A proof-of-concept experiment based on the setup shown in Fig. 1 is carried out. The parameters of the main devices used in the experiment are as follows: the PolM (Versawave Technologies) has a bandwidth of 40 GHz; the DGD of the PMF sections is ~14 ps; the PDs have a 3-dB bandwidth of 45 GHz and a responsivity of 0.4 A/W. The frequency responses of the two microwave filters are measured by a vector network analyzer (VNA) (Agilent E8364A).

Fig. 2 shows the measured results. The measurement is made when the input microwave power is set at 0 dBm. As expected, the two photonic microwave filters have complementary frequency responses. The ACF is then calculated. Thanks to the complementary nature of the frequency responses, a monotonically decreasing ACF in a range from 0.5 to 36 GHz is obtained. A theoretically calculated ACF is also shown in Fig. 2, and an excellent agreement is observed. Since the frequency response of the microwave filter with coefficients of (1, -1) in the low-frequency regime (0–0.5 GHz) is very small, the obtained microwave power in the lower branch has a poor signal-to-noise

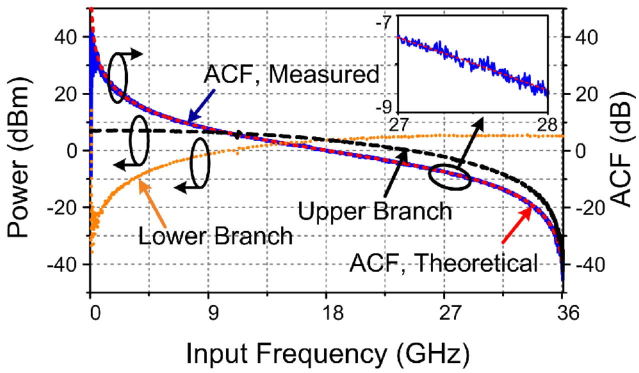

Fig. 2. Measured and calculated power frequency responses of photonic microwave filter pair and ACF based on measured frequency responses. Inset gives zoom-in view of segment of ACF.

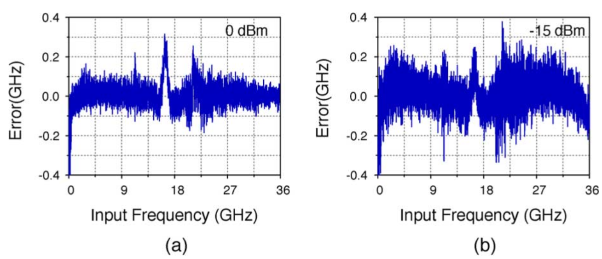

Fig. 3. Measurement errors for two input microwave power levels at (a) 0 dBm, (b) −15 dBm.

ratio. As a result, the system cannot be employed to measure a RF signal with a frequency below 0.5 GHz.

Fig. 3(a) shows the measurement error for the input microwave power of 0 dBm, which is obtained by retrieving the frequencies from the measured ACF based on (5) and comparing them with the actual values. In the frequency range from 0.5 to 36 GHz, the measurement error is within ± 0.2 GHz except for that at around 16 GHz. A relatively large measurement error observed at around 16 GHz is mainly resulted from the imperfections of the electrical devices used in the experiment. If the input microwave power is decreased to −15 dBm, the measurement error is slightly increased, which is still kept within ±0.3 GHz. The measurement error is reduced to ±0.14 GHz for an input signal with a greater power of 5 dBm. It should be noted that the distribution of the measurement error is similar to the spectrum of the system noise, indicating that the measurement error is primarily a result of the system noise, such as the shot noise from the PDs. To reduce the measurement error, a solution is to use high-performance PDs. In addition, the link losses can be optimized to obtain high system accuracy.

To validate the wavelength-independent feature of the scheme, the wavelength of the light wave from the LD is tuned from 1535 to 1570 nm. No significant increase of the measurement error is observed. The stability of the system is also evaluated. To do so, we allow the system to operate in a room environment for a period of 20 minutes; no evident changes in the frequency responses are observed.

IV. Discussion and Conclusion

For the proposed IFM, if multiple signals are received with one signal that has a much higher power, the measurement would give an estimated frequency corresponding to the highest power signal. This feature makes the scheme be potentially used in an adaptive anti-jamming receiver, where the jamming signal has always a much higher power compared with other signals. If the frequency information of the jamming signal is measured by the IFM technique, a tunable notch filter could be used to remove the jamming frequency.

It should be noted that the required power level of the received microwave signal to ensure an acceptable measurement accuracy is still high for practical applications. A possible solution is to use a low-noise microwave amplifier to increase the sensitivity of the system.

In conclusion, a novel technique for IFM using a photonic microwave filter pair with complementary frequency responses was proposed and demonstrated. Thanks to the complementary nature of the frequency responses, a monotonically decreasing ACF extending from 0 to 36 GHz was obtained. Since the filter pair was implemented using a single wavelength, the ACF was independent of the optical wavelength and power, therefore the variations of the wavelength and the power of the LD would have no impact on the measurement accuracy.

References

[1] J. B. Y. Tsui, *Microwave Receivers With Electronic Warfare Applications*. New York: Wiley, 1986.

[2] D. B. Hunter, L. G. Edvell, and M. A. Englund, "Wideband microwave photonic channelised receiver," in *Proc. MWP 2005*, 2005, pp. 249–252.

[3] L. V. T. Nguyen, "Microwave photonic technique for frequency measurement of simultaneous signals," *IEEE Photon. Technol. Lett.*, vol. 21, no. 9, pp. 642–644, May 2009.

[4] H. Chi, X. Zou, and J. P. Yao, "An approach to the measurement of microwave frequency based on optical power monitoring," *IEEE Photon. Technol. Lett.*, vol. 20, no. 14, pp. 1249–1251, Jul. 2008.

[5] X. Zou, H. Chi, and J. P. Yao, "Microwave frequency measurement based on optical power monitoring using a complementary optical filter pair," *IEEE Trans. Microw. Theory Tech.*, vol. 57, no. 2, pp. 505–511, Feb. 2009.

[6] M. V. Drummond, P. Monteiro, and R. N. Nogueira, "Photonic RF instantaneous frequency measurement system by means of a polarization-domain interferometer," *Opt. Expr.*, vol. 17, no. 7, pp. 5433–5438, Mar. 2009.

[7] L. A. Bui, M. D. Pelusi, T. D. Vo, N. Sarkhosh, H. Emami, B. J. Eggleton, and A. Mitchell, "Instantaneous frequency measurement system using optical mixing in highly nonlinear fiber," *Opt. Expr.*, vol. 17, no. 25, pp. 22983–22991, Dec. 2009.

[8] Z. Li, B. Yang, H. Chi, X. M. Zhang, S. L. Zheng, and X. F. Jin, "Photonic instantaneous measurement of microwave frequency using fiber Bragg grating," *Opt. Commun.*, vol. 283, no. 3, pp. 396–399, Feb. 2010.

[9] L. V. T. Nguyen and D. B. Hunter, "A photonic technique for microwave frequency measurement," *IEEE Photon. Technol. Lett.*, vol. 18, no. 10, pp. 1188–1190, May 2006.

[10] H. Emami, N. Sarkhosh, L. A. Bui, and A. Mitchell, "Amplitude independent RF instantaneous frequency measurement system using photonic Hilbert transform," *Opt. Expr.*, vol. 16, no. 18, pp. 13707–13712, Sep. 2008.

[11] M. Attygalle and D. B. Hunter, "Improved photonic technique for broadband radio-frequency measurement," *IEEE Photon. Technol. Lett.*, vol. 21, no. 4, pp. 206–208, Feb. 2009.

[12] S. L. Pan and J. P. Yao, "Instantaneous photonic microwave frequency measurement with a maximized measurement range," in *Proc. MWP 2009*, Valencia, Spain, Oct. 14–16, 2009, paper Fr 4.3.

[13] J. Zhou, S. N. Fu, P. P. Shum, S. Aditya, L. Xia, J. Q. Li, X. Sun, and K. Xu, "Photonic measurement of microwave frequency based on phase modulation," *Opt. Expr.*, vol. 17, no. 9, pp. 7217–7221, Apr. 2009.

[14] X. Zhang, H. Chi, X. Zhang, S. Zheng, X. Jin, and J. P. Yao, "Instantaneous microwave frequency measurement using an optical phase modulator," *IEEE Microw. Wireless Compon. Lett.*, vol. 19, no. 6, pp. 422–424, Jun. 2009.

[15] J. P. Yao, "Microwave photonics," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 314–335, Feb. 2009.