Photonic-assisted approach for instantaneous microwave frequency measurement with tunable range by using Mach-Zehnder interferometers

Dapeng Wang (王大鹏), Kun Xu (徐 坤)*, Jian Dai (戴 键), Zhongle Wu (吴钟乐), Yuefeng Ji (纪越峰), and Jintong Lin (林金桐)

State Key Laboratory of Information Photonics and Optical Communications,
Beijing University of Posts and Telecommunications, Beijing 100876, China
**Corresponding author: xukun@bupt.edu.cn*

Received June 14, 2012; accepted August 8, 2012; posted online January 21, 2013

A novel photonic-assisted approach to microwave frequency measurement is proposed and experimentally demonstrated. The proposed scheme is based on the frequency-to-power mapping with different transmission responses. A polarizer is used in one output branch of a phase modulator to simultaneously implement phase modulation and intensity modulation. Owing to the complementary nature of the transmission responses and the Mach-Zehnder interferometers (MZIs), this scheme theoretically provides high resolution and tunable measurement range. The measurement errors in the experimental results can be kept within 0.2 GHz over a frequency range from 0.1 to 5.3 GHz.

OCIS codes: 060.5625, 060.4510.
doi: 10.3788/COL201311.020604.

Photonic-assisted microwave signal processing system is considered as one of the most important technologies in telecommunication and military applications. Considering the capability of such a system to process large-bandwidth microwave signals even up to 100 GHz, photonic-assisted microwave processing techniques are important factors in modern electronic radar systems. Instantaneous frequency measurement (IFM) is a key component in electronic radar receivers. Information on the adversary can be captured promptly with the aid of the IFM module, thus determining incoming signal frequency nearly in real time. However, the traditional implementations of IFM systems are usually limited by bandwidth, as microwave frequency is unknown and usually varies within about tens of a GHz. A wideband electronic radar receiver entails increasing cost, size, and power consumption. To overcome these limitations, several photonic-assisted approaches were recently proposed[1−11]. These approaches provide inherent advantages such as broadband, low cost, small size, low power consumption, immunity to electromagnetic interference, etc.[12]. The photonic approach for IFMs is attracting increasing interest from researchers worldwide.

Most of previous studies utilized the frequency-to-power mapping relationship of the microwave signal. Such studies derived amplitude comparison functions (ACFs) by comparing different power fading functions. However, the use of long chromatic dispersive medium will introduce great time delay into the system[1−7]. The intensity modulation links used in many works usually need a rigorous electrical direct current bias control circuit to stabilize the modulators operating at the quadrature or null point[8−10]. Furthermore, the IFM systems that use a pair of laser sources or more[8,11] will be subject to measurement errors attributed to the optical power variation in the two optical sources.

In this letter, we propose and experimentally demonstrate a novel photonic-assisted microwave frequency measurement scheme using Mach–Zehnder interferometers (MZIs). The proposed scheme is based on simultaneous phase modulation (PM) and intensity modulation (IM) links and requires a single optical source and modulator. This scheme is free from extra-electrical direct current bias, because no intensity modulator is used. An improved measurement range and resolution is provided because of the complementary nature of the transmission responses. The microwave frequency to be measured can be easily estimated by using ACF, which was established by comparing the transmission responses of the two channels. The measurement range can also be adjusted by tuning the differential time delay of MZI. We experimentally demonstrated the scheme over a frequency range from 0.1 to 5.3 G. The measurement errors were within 0.2 GHz, over this frequency range.

The schematic diagram of the proposed scheme is shown in Fig. 1. A continuous-wave (CW) light from a laser diode (LD) with a wavelength of 1 550.38 nm is injected into a PM driven by a microwave signal. The modulated light is divided into two parts. One part is directly sent to a MZI, whereas the other is adjusted using a polarizer before sending to another MZI. The direction of transmission polarization of the polarizer is aligned at $\pi/4$ relative to the principal axes of the PM. The differential time delays of the two MZIs are the same. The output of the optical signals from the MZIs is sent to the two identical photodetectors (PD), respectively. The ACF is then obtained by comparing the detected microwave power of the two channels. Electrical frequency can be obtained from the unique relationship between

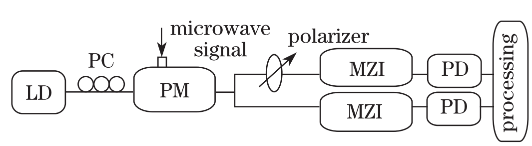

Fig. 1. Schematic diagram of the proposed IFM system.

the frequency and the ACF value. Finally, the information carried by the microwave frequency can be calculated through digital signal processing techniques.

In Fig. 1, when the polarization orientation of the light is aligned at an angle of $\pi/4$ relative to one of the principal axes of the PM using a polarization controller (PC), the upper branch (denoted as IM) becomes an intensity modulation link with interferometric detection. The output radio-frequency (RF) powers under small signal conditions can be expressed as

$$P_{\text{outIM}} \approx 2\alpha_{\text{pol}}^2 \pi^2 I_{\text{DC}}^2 V_{\text{rf}}^2 / V_\pi^2 \cos^2(\pi f \tau) Z_{\text{out}}, \qquad (1)$$

where $\alpha_{\text{pol}} = 0.5$ is the insertion loss of the polarizer; $I_{\text{DC}} = R\alpha_{\text{MZI}}\alpha_{\text{LINK}}\alpha_{\text{PM}}P_0/2$ is the DC current per diode, with R as the diode responsivity, P_0 is the optical power, and α_{MZI}, α_{LINK}, and α_{PM} are the MZI insertion loss, link loss, and PM insertion loss, respectively; V_{rf} is the voltage amplitude; V_π is the voltage required to produce a phase shift of π radians; f is the frequency of the unknown microwave signal; τ is the differential time delay of MZI; Z_{out} is the load impedance.

As a typical phase modulated interferometric detection link, the output of the lower branch denoted as PM under small signal conditions can be expressed as

$$P_{\text{outPM}} \approx 2\pi^2 I_{\text{DC}}^2 V_{\text{rf}}^2 / V_\pi^2 \sin^2(\pi f \tau) Z_{\text{out}}. \qquad (2)$$

From Eqs. (1) and (2), we can obtain ACF for measuring the instantaneous microwave frequency:

$$\text{ACF} = \frac{P_{\text{outIM}}}{P_{\text{outPM}}} = \alpha_{\text{pol}}^2 (\tan^2(\pi f \tau))^{-1}. \qquad (3)$$

In Eq. (3), the ACF is an optical-wavelength-independence function. The relationship between ACF and the microwave frequency is unique in every monotonic region of the power ratio function. Thus, we can obtain the frequency of the input microwave signal from the inverse function of ACF.

A proof-of-concept experiment was performed by using a network analyzer by which the frequency responses of the two branches are measured, as shown in Fig. 2. The CW lightwave from the laser source with a wavelength of

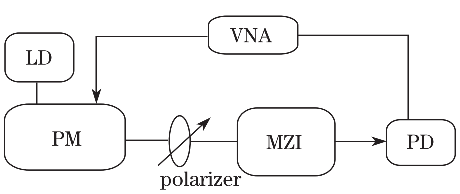

Fig. 2. Experimental setup for the proof of concept. VNA: vector network analyzer.

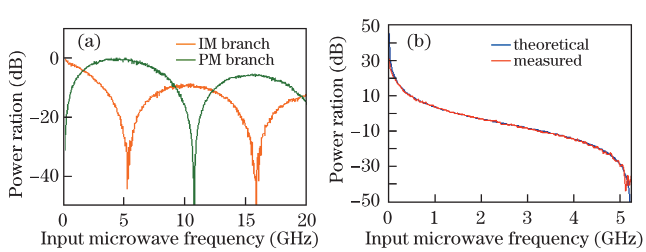

Fig. 3. Measurement results of the proposed IFM system. (a) Measured frequency responses of the photonic IFM link; (b) measured and theoretical ACF curves.

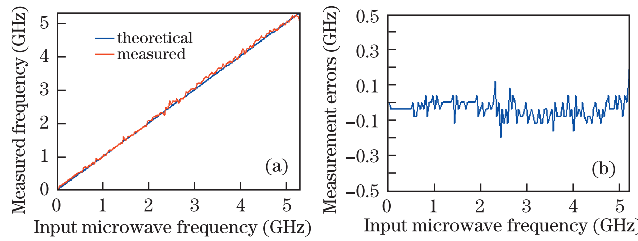

Fig. 4. (a) Measured RF frequency and (b) measured frequency errors.

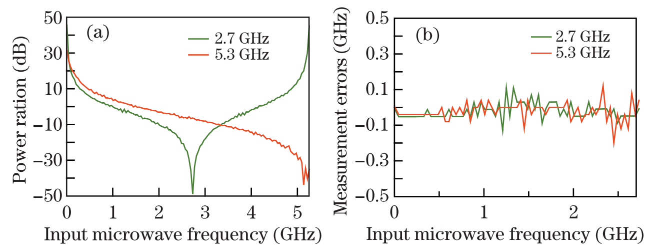

Fig. 5. (a) Measured ACFs for different differential time delays and (b) measured frequency errors for different differential time delays.

1 550 nm was first injected into the 20-GHz phase modulators driven by the network analyzer. After passing through a MZI, with or without a polarizer, the optical signals are converted into electrical signals by the PD. The differential time delays of the MZIs were both 94 ps. The electrical signals were eventually measured by the network analyzer.

The measured ACF and the transfer functions of the two branches are shown in Fig. 3. The measured ACF of the IM branch agrees well with the calculated ACF with a notch at 5.3 GHz. The first notch of the PM branch is complementary to the IM branch as predicted by Eq. (3).

Microwave frequency was estimated using the measured ACF. Figures 4(a) and (b) show the measured frequency, the theoretical frequency, and the measurement errors, respectively. The measurement range was limited to 5.3 GHz by the notch of the ACF functions, as shown in Fig. 3(b). The transmission response of the PM branch monotonously increased, whereas one of the IM branches monotonously decreased, and vice versa. The ACF was steep in each monotonic interval for the complementary nature of the two branches, which reveals a more discernible power variation and a higher measurement resolution compared with the reported scheme[13]. The measurement errors of the proposed scheme were limited to within 0.2 GHz, when the microwave frequency varied from 0 to 5 GHz; whereas in Ref. [13], the errors reach 0.5 GHz in the same frequency range.

The frequency measurement range was limited only by the bandwidth of the PM and the MZIs. The measurement range can be extended much more than the range that this letter demonstrated by using high speed MZIs that provide large differential time delays. However, wide measurement ranges result in more measurement errors. Therefore, a trade-off between broad band and high measurement accuracy must be considered.

This scheme is unambiguous based on entirely different two branches that provide a pair of complementary transmission responses, as the principle of IM signal realization is well interpreted. We used passive MZIs with fixed differential time delays that provide short response time and stabilized performance.

The tunability in the measurement range from 5.3 to 2.7 GHz was also demonstrated by tuning the differential time delay with the MZI. The measured ACFs of the two differential time delays are plotted in Fig. 5. The upper measurement limits were constrained by the differential time delay.

In conclusion, we propose and experimentally demonstrate a novel photonic scheme of instantaneous frequency measurement based on simultaneous phase and intensity modulations. A polarizer is used to implement the simultaneous phase and intensity modulations. Apart from the benefits of assisted photonic technology, the proposed scheme also provides improved measurement range and resolution because of the complementary nature of the transmission responses. The measurement errors can be kept within 0.2 GHz over a frequency range from 0.1 to 5.3 GHz.

This work was supported by the National "973" Program of China (No. 2012CB315705), the National "863" Program of China (No. 2011AA010306), the National Natural Science Foundation of China (Nos. 61107058, 61120106001, 60932004, 61001121, and 60837004), the Beijing Excellent Doctoral Thesis Project (No. YB20101001301), and the Cooperation Project between the Province and Ministries (No. 2011A090200025).

References

1. J. Zhou, S. Fu, S. Aditya, P. P. Shum, and C. Lin, IEEE Photon. Technol. Lett. **21,** 1069 (2009).
2. J. Li, S. Fu, K. Xu, J. Zhou, P. Shum, J. Wu, and J. Lin, Opt. Lett. **34,** 743 (2009).
3. X. Zhang, H. Chi, X. Zhang, S. Zheng, X. Jin, and J. Yao, IEEE Microwave Wireless Compon. Lett. **19,** 422 (2009).
4. L. V. Nguyen and D. B. Hunter, IEEE Photon. Technol. Lett. **18,** 1188 (2006).
5. X. Zou, S. Pan, and J. Yao, J. Lightwave Technol. **27,** 5314 (2009).
6. J. Zhou, S. Fu, P. P. Shum, S. Aditya, L. Xia, J. Li, X. Sun, and K. Xu, Opt. Express **17,** 7217 (2009).
7. P. Wu, X. Han, Y. Gu, S. Li, S. Hu, and M. Zhao, Chin. Opt. Lett. **9,** 081301 (2011)
8. J. Dong, Y. Yu, X. Zhang, and D. Huang, Chin. Opt. Lett. **9,** 051202 (2011)
9. H. Chi, X. Zou, and J. Yao, IEEE Photon. Technol. Lett. **20,** 1249 (2008).
10. H. Guo, G. Xiao, N. Mrad, and J. Yao, IEEE Photon. Technol. Lett. **21,** 45 (2009).
11. X. Zou and J. Yao, IEEE Photon. Technol. Lett. **20,** 1989 (2008).
12. A. J. Seeds and K. J. Williams, J. Lightwave Technol. **24,** 4628 (2006).
13. K. Xu, J. Dai, R. Duan, Y. Dai, Y. Li, J. Wu, and J. Lin, IEEE Photon. Technol. Lett. **23,** 1328 (2011).