High-Resolution Frequency Identification of Wideband Microwave Signal Using a Hybrid Optical Filter

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Abstract: We propose a photonic approach for frequency identification of broadband microwave signal with a high resolution using a hybrid optical filter. A frequency resolution of 20 MHz and a measurement accuracy of 5.6 MHz are experimentally demonstrated within a measurement range of 2-35 GHz.

1. Introduction

Frequency identification of broadband microwave or millimeter-wave signals is a very important measurement task in modern electronic systems, including high-resolution radar, electronic warfare, high-speed communication, and cognitive radio systems [1]. In recent years, the explosive growth of data traffic promotes the electronic systems toward high carrier frequency and broad bandwidth, bringing urgent demands to microwave frequency identification in terms of wide measurement range and high frequency resolution. Conventionally, microwave frequency identification is realized based on electronic instruments, such as electrical spectrum analyzer or oscilloscope. These electronic-based techniques can achieve a high frequency resolution but suffer from relatively narrow frequency measurement range, high power consumption, and vulnerability to electromagnetic interference (EMI).

Recently, photonics-assisted microwave frequency identification techniques have attracted considerable attentions, which identifies the frequency of microwave signals in the optical domain, holding unique advantages of wide measurement range, ultra-fast measurement speed, low power consumption, and immunity to EMI [2]. Generally, photonics-assisted microwave frequency measurement techniques can be mainly divided into two categories: frequency-to-power mapping (FPM) and frequency-to-time mapping (FTM). For the FPM-based techniques, an amplitude comparison function (ACF) is constructed with the help of a complementary filter pair [3], an optical mixing unit [4], or a dispersive delay element [5]. By monitoring the optical power fluctuation, the frequency of the microwave signal can be extracted accurately with the aid of the measured ACF. The FPM-based techniques can achieve an ultrahigh measurement speed, but they can only measure single-frequency microwave signal, which restricts their applications in some fields where multi-frequency measurement is required. For the FTM-based techniques, the frequency of the microwave signal is linearly converted to an electrical time delay with the help of a narrowband tunable optical filter [6], a dispersive Fourier transformer [7], or a frequency shifting recirculating delay line [8]. By measuring the delay change of the electrical pulse, the frequency of the microwave signals can be obtained. The FTM-based techniques are capable of measuring multi-frequency signals, making them suitable for some application scenarios where complex interference signals need to be captured. Recently, an FTM-based adaptive microwave frequency identification technique has also been proposed with the help of an integrated silicon photonic scanning filter, which has the unique capability of identifying the type of the microwave signals [9]. This technique makes it possible for feature extraction of broadband microwave signals, but its frequency resolution is only 375 MHz, which is determined by the Q factor of the scanning filter.

In this paper, we propose a photonic method for frequency identification of broadband microwave signal with a high resolution using a hybrid optical filter. In the experiment, a frequency resolution of 20 MHz, a measurement accuracy of 5.6 MHz and a measurement range of 2-35 GHz are realized. The proposed system exhibits a capability to identify single-frequency (SF) signal and complex microwave signals, including multiple-frequency (MF), frequency-hopping (FH), chirped-frequency (CF) signals, as well as their combinations.

2. Principle

Figure 1(a) illustrates the schematic of the proposed broadband microwave frequency identification system. As can be seen, a continuous-wave (CW) optical carrier generated by a tunable laser source (TLS) is sent to a Mach-Zehnder modulator (MZM) via a polarization controller (PC1). The unknown microwave signal is modulated on the optical carrier by the MZM. The modulated signal is launched into a hybrid optical filter, which consists of a fiber ring resonator (FRR) and an integrated silicon racetrack microring resonator (MRR). The FRR has a 3-dB bandwidth of 7.7 MHz and a free spectral range (FSR) of 478 MHz. The MRR has a 3-dB bandwidth of 200 MHz and a FSR of 72.5 GHz. In the experiment, the FRR is connected in series with the MRR. As shown in Fig. 1(b), when the resonance wavelengths of the FRR and MRR are matched, one of the resonance peaks of the FRR will be selected, where an optical filter with an ultrahigh-Q factor and a large FSR is realized. When the optical filter is used in the broadband microwave frequency identification system, a high frequency resolution and a wide measurement range can be achieved simultaneously. The optical signal at the drop port of the MRR is amplified by an erbium-doped fiber amplifier (EDFA), which is followed by a tunable optical bandpass filter (OBPF) with a bandwidth of 50 GHz to remove the amplified spontaneous emission (ASE) noise. The optical signal at the output of the OBPF is then fed into an avalanche photodiode (APD). The electrical signal generated by the APD is recoded by an oscilloscope. As shown in Fig. 1(c), to achieve broadband microwave frequency identification, the wavelength of the TLS is linearly scanned. The center wavelength of the ultrahigh-Q optical filter is fixed and its value is properly set. When the optical carrier and -1st-order sideband of the modulated optical signal is swept across the optical filter, two electrical pulses will be generated after the APD. Therefore, by measuring the time interval between the two electrical pulses, the frequency of the microwave signal can be extracted accurately.

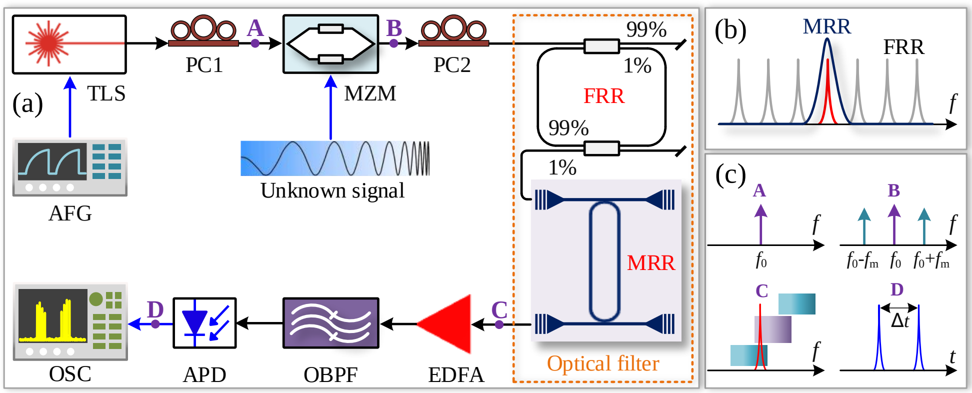

Fig. 1. Schematic of the proposed microwave frequency identification system.

3. Experimental results

Firstly, the performance of the proposed system is evaluated by measuring SF microwave signals, whose frequencies are changed from 2 GHz to 35 GHz with a step of 0.375 GHz. Figure 2(a) shows the estimated microwave frequency versus the actual input microwave frequency for each of the test tones, which indicates that the proposed system is capable of accurately identifying microwave frequencies range from 2 to 35 GHz. Figure 2(b) gives the frequency estimation errors within the whole frequency measurement range. The root mean square (RMS) value of the frequency estimation errors is calculated to be 5.6 MHz. To evaluate the frequency resolution of the proposed system, a two-tone microwave signal with frequencies of 18 GHz and 18.02 GHz is injected into the system, and the measurement result is shown in Fig. 2(c). As can be seen, the two frequency components are separated clearly, showing that the frequency resolution of the proposed system is better than 20 MHz.

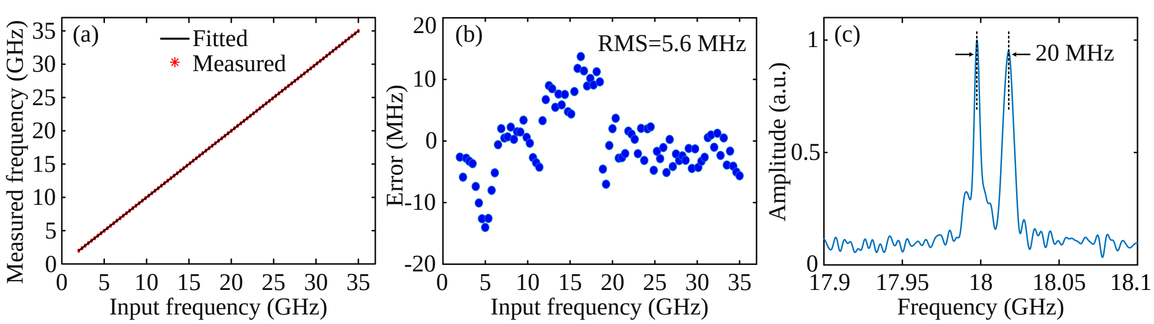

Fig. 2. (a) Frequency estimation measurement range from 2 to 35 GHz; (b) Frequency estimation errors within 2-35 GHz, showing an RMS value of 5.6 MHz; (c) Measurement result of a two-tone signal with a frequency spacing of 20 MHz.

Subsequently, the proposed system is employed to measure broadband microwave signals. To verify the capability of MF signal measurement, a three-tone microwave signal with frequencies of 17.5 GHz, 18 GHz, and

18.5 GHz is injected into the system, and the measurement result is shown in Fig. 3(a). The estimated frequencies of the three components are 17.51 GHz, 18.01 GHz, and 18.51 GHz, verifying the ultrahigh measurement accuracy provided by the system. Then, a FH signal with three frequency steps of 17.5 GHz, 18 GHz, and 18.5 GHz is also measured. The measurement result is shown in Fig. 3(b). Three filled pulses are captured, which is different from the results given in Fig. 3(a), where three hollow pulses are measured. Therefore, we can distinguish the MF signal and the FH signal by judging whether the pulse envelope is continuous or discrete. According to the principle of statistical measurement [9], if the measured pulse is hollow, we can judge that it is a time-invariant signal; if the measured pulse is filled with random powers, we can judge that it is a time-variant signal. Then, a CF signal with a center frequency of 16 GHz and a bandwidth of 7 GHz is also measured. The result is shown in Fig. 3(c). The measured waveform is also filled with random powers, which means that it is a time-variant signal. The proposed system is capable of identifying more complex microwave signal, such as a combination of multitype microwave signals. As a demonstration, a complex microwave signal consisting of a FH signal (9.5 GHz, 10.5 GHz, and 11.5 GHz), a CF signal (16.5-21.5 GHz) and a MF signal (26.5 GHz, 29 GHz, and 31.5 GHz) is measured by the proposed system, as shown in Fig. 3(d). As can be seen, both the frequency and the type of the microwave signals can be extracted accurately.

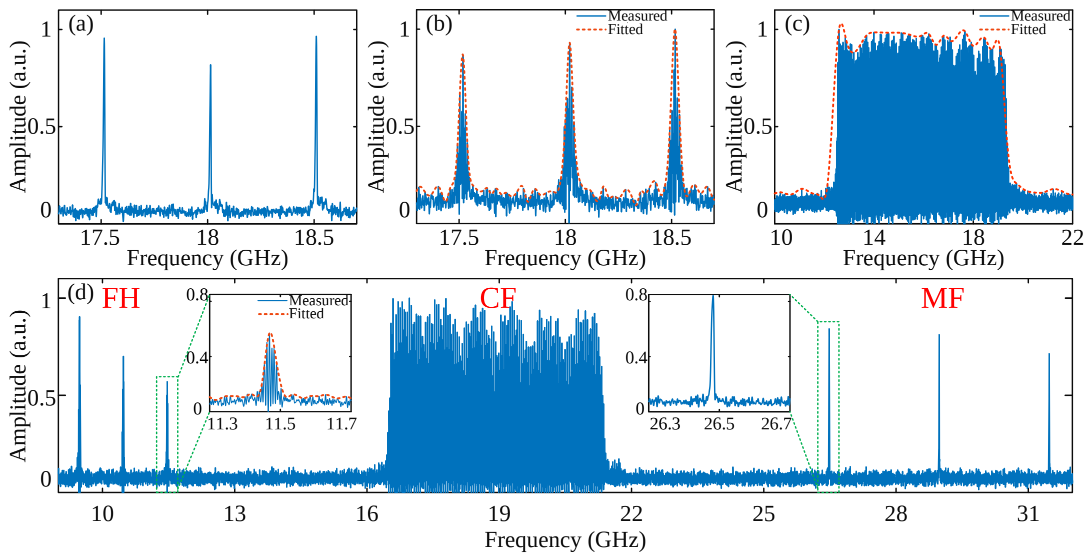

Fig. 3. (a) Measurement result of MF microwave signal with frequencies of 17.5 GHz, 18 GHz, and 18.5 GHz; (b) Measurement result of FH microwave signal with frequency steps of 17.5 GHz, 18 GHz, and 18.5 GHz; (c) Measurement result of CF microwave signal with a center frequency of 16 GHz and a bandwidth of 7 GHz; (d) Measurement result of the combination of multitype microwave signals.

4. Conclusion

A method for frequency identification of broadband microwave signal with a high resolution was proposed and experimentally demonstrated. A frequency resolution of 20 MHz, a measurement accuracy of 5.6 MHz and a measurement range of 2-35 GHz are realized. The proposed system is promising to be widely used in high-resolution radar, electronic warfare, high-speed communications, and cognitive radio systems.

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6. References

[1] A.E. Spezio, IEEE Trans. Micro. Theory Tech. **50**, 633-644 (2002).
[2] J. Yao, J. Lightwave Technol. **27**, 314-335 (2009).
[3] X. Zou, et al., IEEE Trans. Micro. Theory Tech. **57**, 505-511 (2009).
[4] H. Emami, et al., IEEE Trans. Micro. Theory Tech. **62**, 2462-2470 (2014).
[5] W. Li, et al., IEEE Photon. J. **4**, 427-436 (2012).
[6] F. Zhou, et al., IEEE Photon. J. **10**, 1-7 (2018).
[7] L. V. T. Nguyen, IEEE Photon. Technol. Lett. **21**, 642-644 (2009).
[8] T. A. Nguyen, et al., Opt. Letts. **39**, 2419-2422 (2014).
[9] X. Wang, et al., Photonics Res. **7**, 172-181. (2019).