Microwave Frequency Measurement Based on Optical Power Monitoring Using a Complementary Optical Filter Pair

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***Abstract*—An approach to the measurement of a microwave frequency based on optical power monitoring using a complementary optical filter pair is proposed and investigated. In the proposed system, a microwave signal is applied to a Mach–Zehnder modulator, which is biased at the minimum transmission point to suppress the optical carrier. The carrier-suppressed optical signal is then sent to the complementary optical filter pair, with the powers from the complementary filters measured by two optical power meters. A mathematical expression that relates the microwave frequency and the optical powers is developed. Experiments are performed to verify the effectiveness of the proposed approach. The performance of the proposed system in terms of the frequency measurement range, operation stability, and robustness to noise is also investigated.**

***Index Terms*—Frequency measurement, microwave photonics, optical microwave signal processing.**

I. Introduction

MICROWAVE frequency measurement can find many important applications in civil and defense systems. Microwave frequency measurement based on an electronic spectrum analyzer can provide a measurement range from a few gigahertz to a few tens of gigahertz [1]–[3], which can be extended to over a few hundred gigahertz if an electronic mixer is employed, but the technique is usually limited to low-speed frequency measurement due to the frequency-sweeping operation of the electronic spectrum analyzer. For applications such as in a warfare system, wideband and real-time frequency measurement is required. Thanks to the inherent broadband width offered by modern optics, frequency measurement based on photonics techniques has the potential to achieve broadband and instantaneous frequency measurement. Recently, a few photonics-based approaches have been proposed [4]–[11]. These approaches can offer a near real-time frequency measurement in a large bandwidth from several gigahertz to a hundred gigahertz. In addition, photonics-based microwave frequency measurement can also offer additional advantages such as the immunity to electromagnetic interference, low loss, and small size. These advantageous features make the photonics-based approaches a potential solution to broadband and instantaneous frequency measurement for applications in warfare systems.

In [4], a tunable Fabry–Perot interferometer was used as an optical scanning receiver for microwave frequency measurement. Microwave frequency can also be measured using a phased array consisting of electrooptic waveguide delay lines [5], a high-resolution free-space diffraction grating [6], an array of phase-shifted gratings [7], an integrated Bragg-grating together with a Fresnel lens system [8], or an etalon combined with a wavelength splitter [9], all acting as an optical channelizer. Recently, a technique was proposed to measure the microwave frequency by comparing two different dispersion-induced power penalties from two intensity-modulated double-sideband optical signals that are propagating through a dispersive medium [10]. The technique was improved with adjustable frequency measurement range and resolution by tuning the wavelength spacing [11].

An approach to microwave frequency measurement was also proposed recently by the authors of this paper [12]. Instead of using a dispersive component, as was done in [10] and [11], an optical comb filter with a sinusoidal spectral response was employed. The microwave frequency was estimated by monitoring the optical powers of two carrier-suppressed sidebands that were located at the peak and the valley of the sinusoidal spectral response. The major limitation associated with the technique in [12] was the need for two optical sources that should be precisely controlled to have stable optical powers and wavelengths. Any power fluctuations and wavelength drifts of the two light sources would lead to a large frequency measurement error.

To solve this problem, in this paper we propose a novel technique that uses only one single wavelength from one light source. In the proposed system, a microwave signal with its frequency to be measured is applied to a Mach–Zehnder modulator, which is biased at the minimum transmission point to suppress the optical carrier. The output from the Mach–Zehnder modulator is then sent to an optical comb filter pair with complementary spectral responses. The microwave frequency is measured by monitoring the filtered optical powers via two optical power meters. A mathematical expression that

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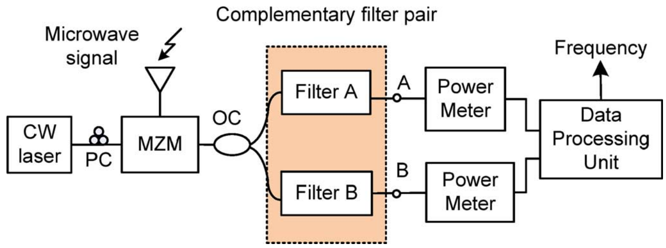

Fig. 1. Schematic of the proposed photonic microwave frequency measurement system. Mach–Zehnder modulator: MZM. Polarization controller: PC. Optical coupler: OC.

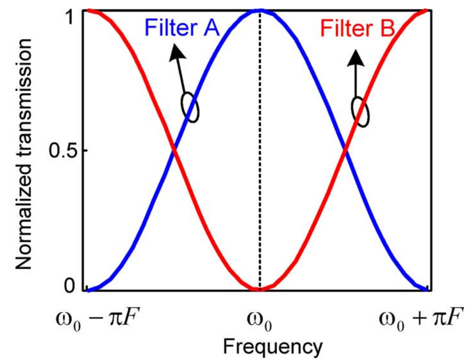

Fig. 2. Transmission responses of the complementary filter pair. F (in hertz) is the FSR of the filter pair.

relates the microwave frequency and the optical powers is derived. Proof-of-concept experiments are performed, and the effectiveness of this approach is experimentally verified. In addition to the advantage of using a single wavelength, the proposed approach has another advantage: the measured microwave frequency is independent of the power of the optical source, which makes the frequency measurement insensitive to the power fluctuations of the light source, leading to a better frequency measurement accuracy. The performance of the system, including the frequency measurement range, operation stability, and robustness to noise is investigated as well.

II. Principle

The proposed approach is schematically shown in Fig. 1. The system consists of a continuous wave (CW) light source, a Mach–Zehnder modulator, a complementary optical filter pair, and two optical power meters. A microwave signal with an unknown frequency is applied to the Mach–Zehnder modulator via the RF port. The Mach–Zehnder modulator is biased at the minimum transmission point of the transfer function such that the optical carrier is completely suppressed and only the first-order sidebands would be generated under small-signal modulation condition. The two first-order optical sidebands are then sent to the complementary filter pair (Filters A and B). The optical powers of the two optical sidebands are monitored by two optical power meters. Thanks to the complementary nature of the transmission responses, as shown in Fig. 2, a fixed relationship between the microwave frequency and the optical powers is established, which enables the measurement of the microwave frequency by monitoring the optical powers. In the following, a more detailed theoretical analysis will be presented.

For a Mach–Zehnder modulator that is biased at the minimum transmission point, the optical carrier is completely suppressed. Under the small-signal modulation condition, at the output of the Mach–Zehnder modulator we will have only the two first-order sidebands. The light field $E(t)$ at the output of the modulator is expressed as

$$E(t) = j\sqrt{P_0}J_1(\beta)\exp(j\omega t) \times [\exp(-j\Omega t) + \exp(j\Omega t)] \tag{1}$$

where ω and Ω are, respectively, the angular frequencies of the CW laser and the microwave signal, P_0 is the output optical power of the laser source, $J_1(\cdot)$ is the first-order Bessel function of the first kind, $\beta = \pi \times (V_m/V_\pi)$ is the modulation depth, V_m is the amplitude voltage of the microwave signal, and V_π is the half-wave voltage of the Mach–Zehnder modulator.

Assume that each of the complementary filters has a transmission response that can be expressed in the form of a sinusoidal function. Considering the frequency of the optical carrier is located at ω_0, the offset $\omega - \omega_0 = \Omega$ is the microwave frequency, we have the transmission responses

$$T_A = [1 + \gamma\cos(\Omega/F)]/2 \tag{2a}$$

and

$$T_B = [1 - \gamma\cos(\Omega/F)]/2 \tag{2b}$$

where $\gamma = (T_{\max} - T_{\min})/T_{\max} + T_{\min})$ is the relative peak-to-notch contrast ratio, $T_{\max}$ and $T_{\min}$ are, respectively, the maximum and minimum transmissions of the filters, and F is the free spectral range (FSR) of the filter pair.

By combining (1) and (2a) and (2b), we can get the optical powers at ports A and B

$$P_A = P_0[J_1(\beta)]^2[1 + \gamma\cos(\Omega/F)] \tag{3a}$$

and

$$P_B = P_0[J_1(\beta)]^2[1 - \gamma\cos(\Omega/F)]. \tag{3b}$$

Based on (3a) and (3b), we obtain a ratio between the output optical powers

$$R_1 = \frac{P_B}{P_A} = \frac{1 - \gamma\cos(\Omega/F)}{1 + \gamma\cos(\Omega/F)} \tag{4a}$$

or

$$R_2 = \frac{P_A}{P_B} = \frac{1 + \gamma\cos(\Omega/F)}{1 - \gamma\cos(\Omega/F)}. \tag{4b}$$

As can be seen, both the optical power and the microwave power (the Bessel function) are eliminated in (4a) and (4b) and the power ratio is only a function of the microwave frequency.

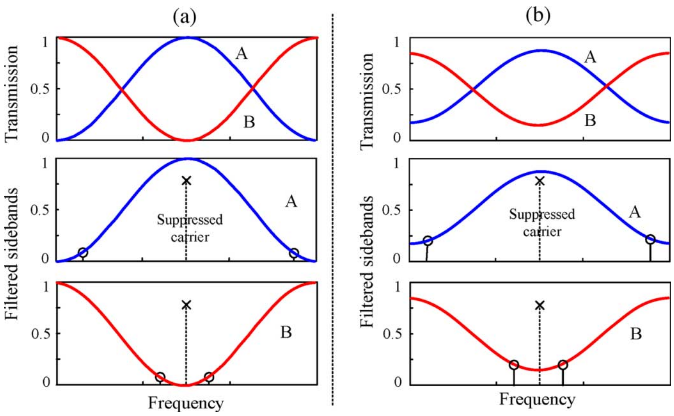

Fig. 3. Impact of the relative peak-to-notch contrast ratio γ on the filtered optical sidebands.

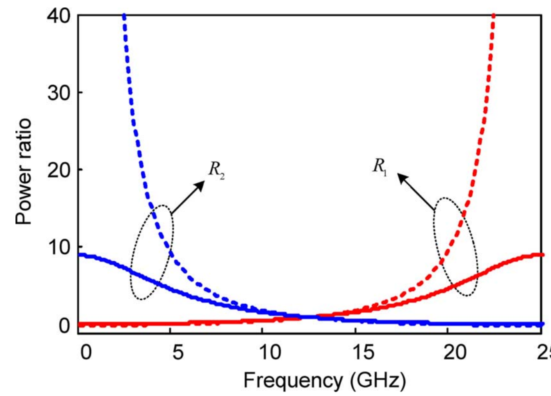

Fig. 4. Power ratios for $\gamma = 1$ (dotted lines) and $\gamma = 0.8$ (solid lines).

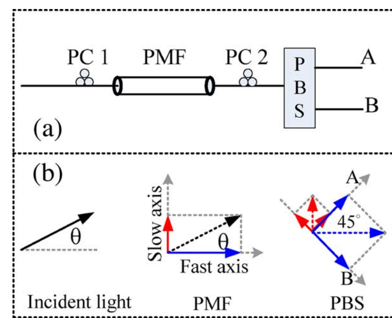

Fig. 5. (a) Diagram of the complementary filter pair. (b) Polarization states of the lightwaves along the fiber. Polarization controller: PC. Polarization-maintaining fiber: PMF. Polarization beam splitter: PBS.

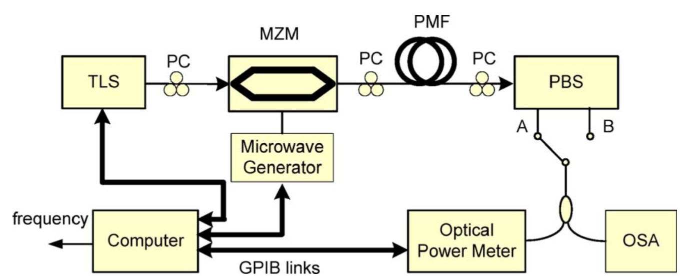

Fig. 6. Experimental setup for the proposed frequency measurement. Tunable laser source: TLS. Mach–Zehnder modulator: MZM. Polarization controller: PC. Polarization-maintaining fiber: PMF. Polarization beam splitter: PBS. Optical spectrum analyzer: OSA. General purpose interface bus: GPIB.

Therefore, the microwave frequency can be estimated by monitoring the optical powers. A distinct feature of the approach is that the microwave frequency is independent of the power of the optical source, which makes the system have a good robustness to optical power fluctuations. While in [12], two independent laser sources were employed, the power fluctuations would be reflected in the frequency measurement, leading to a poor measurement accuracy. Therefore, the proposed system can be greatly simplified without the need for high-precision control of the laser source to stabilize the output optical power. In addition, the use of a single light source would make it much easier to locate the optical carrier at the central frequency of the complementary filter pair, which again would increase the measurement accuracy.

Next, we will analyze the impact of the relative peak-to-notch contrast ratio γ on the accuracy of the frequency measurement. In Fig. 3, the transmission responses for $\gamma = 1$ and $\gamma = 0.8$ are shown. As can be seen when $\gamma = 1$, the power of the filtered sidebands approaches zero when the microwave frequency is close to zero for Filter B and close to half of the FSR for Filter A. This indicates that the signal-to-noise ratio (SNR) at these regions is poor, leading to a large measurement error. When the relative peak-to-notch contrast ratio is reduced, e.g., $\gamma = 0.8$, the output powers have higher values throughout the entire frequency range, as a result the measurement error is reduced. In addition, a smaller γ would also lead to an increased frequency measurement range. As can be seen from Fig. 4, the frequency measurement range for $\gamma = 0.8$ is larger than that for $\gamma = 1$.

III. Experiment

Experiments are performed to verify the effectiveness of the technique and to study the system performance. The key component in the system is the complementary filter pair, which is implemented by using a length of polarization-maintaining fiber, in conjunction with two polarization controllers and a polarization beam splitter, as show in Fig. 5. The polarization direction of a linearly polarized lightwave from the laser source is aligned by the first polarization controller with an angle of θ with respect to the fast axis of the polarization-maintaining fiber, which is projected to the principal axes with one traveling along the fast axis and the other along the slow axis. Due to the birefringence of the polarization-maintaining fiber, a time-delay difference between the two orthogonally polarized lightwaves is generated. A second polarization controller is connected after the polarization-maintaining fiber to adjust the two lightwaves to have an angle of 45° with respect to the axes of the polarization beam splitter. Two transmission responses at ports A and B expressed in (2a) and (2b) are obtained. The relative peak-to-notch contrast ratio of the complementary filters can be adjusted by tuning the incident angle θ. The relationship between γ and θ is given by $\gamma = 2\tan(\theta)/[1+\tan^2(\theta)]$.

The experimental setup is shown in Fig. 6. A lightwave from a tunable laser source (Anritsu MG9638A) is modulated at a Mach–Zehnder modulator (JDS-Uniphase) by a microwave signal with its frequency to be measured, which is generated by a microwave generator (Agilent E8254A). A dc bias is

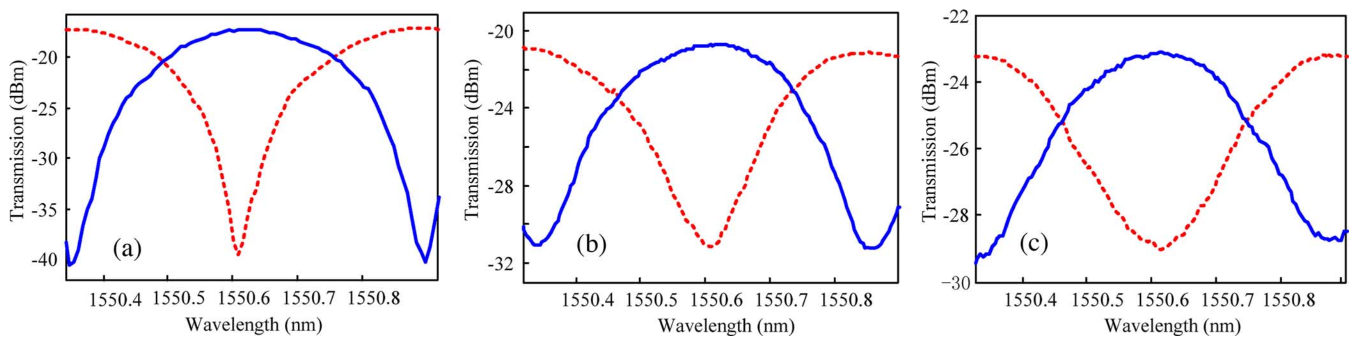

Fig. 7. Transmission responses (measured at ports A and B) with different absolute peak-to-notch contrast ratios. (a) 23 dB. (b) 10.2 dB. (c) 6 dB.

applied to the Mach–Zehnder modulator to suppress the optical carrier. The carrier-suppressed optical signal is then sent to the complementary filter pair. At the outputs of the complementary filter pair, the optical powers are monitored by the optical power meter (Agilent 8163B) with the measured data analyzed by a data processing unit. Note that the tunable laser source, the microwave signal generator, and the optical power meter are controlled by a computer via general purpose interface bus (GPIB) interfaces, which enables a fast and accurate measurement.

In the first experiment, we investigate the frequency measurement for a complementary filter pair with different relative contrast ratios. In the experiment, the output power of the tunable laser is set as 6 dBm and the complementary filter pair is designed to have an FSR of 66 GHz. By adjusting the first polarization controller, the polarization angle θ is adjusted. As shown in Fig. 7, the transmission responses of the filters having a relative peak-to-notch contrast ratio of $\gamma = 0.99, 0.825$, or 0.6, or an absolute peak-to-notch contrast ratio of 23, 10.2, or 6 dB, are achieved, where the absolute peak-to-notch contrast ratio is given by $R = 10\log[(1+\gamma)/(1-\gamma)] = 10\log(T_{\max}/T_{\min})$. Under these contrast ratios, we increase the frequency and the power of the microwave signal and measure the optical powers from ports A and B.

The measured microwave frequency and the measurement errors under the three contrast ratios are shown in Fig. 8. From Fig. 8(a) we can see, the power distributions of both P_A and P_B reflect the complementary nature of the transmission responses having a relative peak-to-notch contrast ratio of 0.825. The ratios R_1 and R_2 based on the measured data are compared with the theoretical calculations in Fig. 8(b), and a good agreement is observed. In Fig. 8(c), the estimated measurement errors are less than ± 0.2 GHz within a measurement range of 2–24 GHz. In addition, the measurement errors for the complementary optical filter pair with relative peak-to-notch contrast ratios of 0.99 and 0.6 are also given, as shown in Fig. 8(d) and (e), to illustrate the impact of the relative peak-to-notch contrast ratio. Two corresponding measurement ranges, 2–20 and 1–26 GHz, are obtained with the same measurement error less than ± 0.2 GHz. Hence, a larger measurement range is observed for a smaller relative peak-to-notch contrast ratio. These results show that the proposed approach is able to measure a microwave frequency at different power levels, and a smaller γ can provide a larger measurement range. Note that the measurement ranges are less than half of the FSR. This is due to the limited bandwidth of the Mach–Zehnder modulator used. Theoretically, a measurement range as large as half of the FSR can be achieved.

In the second experiment, the maximum frequency measurement range is investigated. To do so, we design a complementary filter pair with a smaller FSR of 26 GHz to avoid that the measurement range is limited by the bandwidth of the Mach–Zehnder modulator. The relative peak-to-notch contrast ratio of the filter is $\gamma = 0.833$ or an absolute peak-to-notch contrast ratio is 10.4 dB. We also increase the frequency and the power of the microwave signal during this experiment. The transmission spectrum is shown in Fig. 9(a). The optical powers at the output of the complementary filter pair are shown in Fig. 9(b). Fig. 9(c) shows the measured and theoretical power ratios. The measurement error distribution is shown in Fig. 9(d). We can see that a measurement range of 1–12 GHz, which is close to half of the FSR, is obtained for $\gamma = 0.833$. Although this measurement range is smaller than those in the first experiment, it is conducted to show that a measurement range of half FSR can be achieved with a relatively smaller γ.

The key advantage of this technique is that the frequency measurement is insensitive to the optical power fluctuations. To verify this conclusion, in the experiment we increase the power of the tunable laser source from 6 to 8 dBm with other parameters being kept the same as those used in Fig. 8(a). The results show that although the measured optical powers P_A and P_B are increased due to the power increase of the tunable laser source, the measured microwave frequency and measurement error are still with the same distributions.

IV. Stability and Robustness to Noise

The stability and robustness to noise are two important factors that would affect the performance of the proposed frequency measurement system.

A. *Stability*

In the experimental setup, the complementary filter pair is implemented using a length of polarization-maintaining fiber in conjunction with two polarization controllers and a polarization beam splitter to control the polarization states of the lightwaves in the fiber. It is known that the polarization state of a lightwave traveling in the fiber would be altered when the environment conditions are changed, which would affected the accuracy of the frequency measurement. In the experiment, the

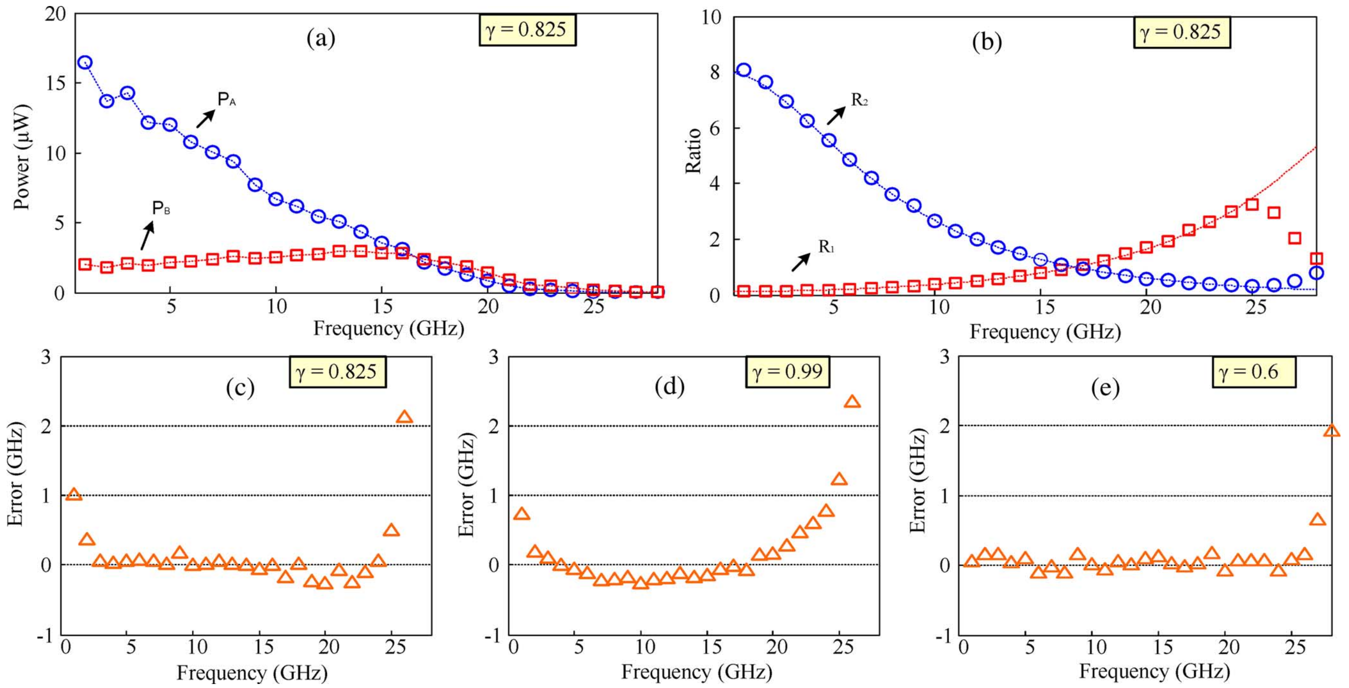

Fig. 8. Measurement error analysis for a complementary filter pair with different contrast ratios. (a) Measured optical powers for a relative peak-to-notch contrast ratio of 0.825. (b) Calculated power ratios (squares and circles) based on the measured data and theoretical ratios (dotted lines). (c) Measurement errors for a relative peak-to-notch contrast ratio of 0.825. (d) Measurement errors for a relative peak-to-notch contrast ratio of 0.99. (e) Measurement errors for a relative peak-to-notch contrast ratio of 0.6.

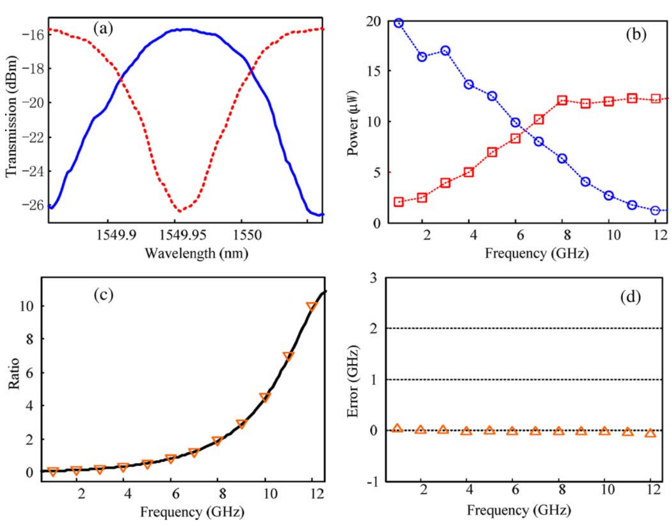

Fig. 9. (a) Transmission response of the complementary filter pair with an FSR of 26 GHz. (b) Measured powers: the circles and squares represent the measured P_A and P_B respectively. (c) Measured power ratio (triangles) and theoretical values (solid line) of R_1. (d) Distribution of measurement errors.

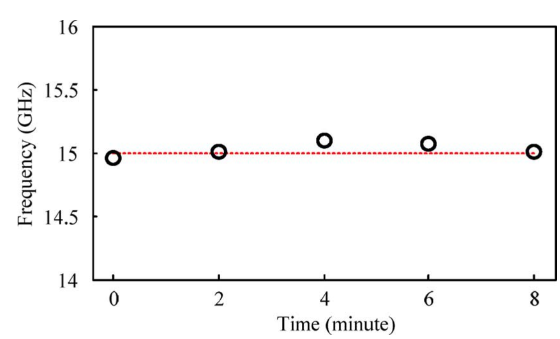

Fig. 10. Measured frequencies at five times with a time interval of 2 min.

output powers are measured by the power meter with the data recorded in a data processing unit. The data are collected within 2 min via GPIB interfaces. To show the short-term stability during measurement operations, an optical spectrum analyzer (shown in Fig. 6) is connected to the outputs of the polarization beam splitter to monitor the optical spectra. By observing the distributions of the optical sidebands, we are able to evaluate the stability of the system. For a given microwave frequency of 15 GHz, the optical spectra at ports A and B are measured for five different times with a time interval of 2 min. Based on the five measured optical spectra, the estimated frequencies at five times are compared with the target frequency (15 GHz), as shown in Fig. 10. The measurement errors are less than ±0.2 GHz, and a good short-term stability is further confirmed.

The long-term stability is theoretically studied. The key component in the system that is sensitive to temperature changes is the polarization-maintaining fiber. When the temperature changes, the birefringence of the polarization-maintaining fiber will change, leading to the change of the frequency responses of the complementary filter pair. The frequency measurement errors due to the change of the polarization-maintaining fiber birefringence are calculated. Assume the complementary filter pair is implemented using a polarization-maintaining fiber with a temperature-dependent birefringence coefficient of

$d\Delta n/dT = -7\times10^{-8}/K$ [13] and an FSR of 66 GHz, the frequency drift of the frequency responses of the complementary filter pair due to the temperature change can be expressed as

$$\Delta\Omega = \left(2\pi c\Delta T L_B/\lambda_0^2\right)\times d\Delta n/dT \quad (5)$$

where c and λ_0 are the light velocity and light wavelength in vacuum, ΔT is the temperature change, and L_B is the beating length of the polarization-maintaining fiber.

Based on (4a) and (4b) and (5), to ensure a measurement error less than 5% of the target frequency, a temperature stability of ± 0.12 °C is required. This temperature stability can be easily achieved using a commercially available temperature controller. In addition, the stability of the system can be improved if a high-temperature tolerance polarization-maintaining fiber is utilized such as the polarization-maintaining photonic-crystal fiber with a temperature-dependent birefringence coefficient as small as $d\Delta n/dT = -2\times10^{-9}/K$ [13]. For a system using the polarization-maintaining photonic-crystal fiber, to ensure a measurement error less than 5%, a temperature stability of ± 2 °C is required.

The stability can also be improved if the complementary filter pair is implemented using an unbalanced Mach–Zehnder interferometer made in optical waveguides [14], [15].

B. Robustness to Noise

As discussed in Section II, the SNR is poorer when the sidebands are located close to the minimum transmission points of the transmission responses. A solution to improve the SNR is to use a filter pair with a smaller relative peak-to-notch contrast ratio. Assume an instantaneous noise field follows a Gaussian distribution in the case of the central limit theorem [16], although several independent noise sources (such as the shot noise, relative intensity noise, and thermal noise) are all contributing to the total noise. Therefore, by taking this Gaussian noise into account, (4a) can be rewritten as

$$R_1 = \frac{P_0\left[J_1(\beta)\right]^2\left[1-\gamma\cos(\Omega/F)\right]+0.5\left[V_{BC}^2+V_{BS}^2\right]}{P_0\left[J_1(\beta)\right]^2\left[1+\gamma\cos(\Omega/F)\right]+0.5\left[V_{AC}^2+V_{AS}^2\right]} \quad (6)$$

where V_{AC} and V_{AS} (or V_{BC} and V_{BS}) are the in-phase and quadrature components of the instantaneous Gaussian noise for port A (or B). The SNR is given by

$$\alpha_A = P_0\left[J_1(\beta)\right]^2\left[1+\gamma\cos(\Omega/F)\right]/(\sigma_A)^2 \quad (7a)$$

or

$$\alpha_B = P_0\left[J_1(\beta)\right]^2\left[1-\gamma\cos(\Omega/F)\right]/(\sigma_B)^2 \quad (7b)$$

where σ_A^2 (or σ_B^2) is the standard deviation of V_{AC} and V_{AS} (or V_{BC} and V_{BS}). According to (6) and (7a) and (7b), the noise-induced measurement errors obtained by simulations are shown in Fig. 11. We can see that most errors are less than ± 0.2 GHz when $\alpha_A = \alpha_B = 16.5$dB, which is used as the required minimum SNR here. When the SNR drops to 11 dB, the measurement errors increase to ± 0.8 GHz.

When the output power of the tunable laser source is 6 dBm and the noise floor of the optical power meter is -70 dBm, with a measurement range from $+28$ to -70 dBm, a power margin of 59.5 dB is provided under a minimum SNR of 16.5 dB. For the complementary filter pair, the loss of the transmission response is below 20 dB from $0.032F$ to $0.0468F$ for $\gamma = 1$, or 10 dB in the entire half FSR for $\gamma = 0.8$. By incorporating the power margin and the loss of the complementary filter pair, the system can operate if the modulation depth in (1) is greater than 0.021 for $\gamma = 1$, or greater than 0.0068 for $\gamma = 0.8$. For example, at a frequency of 1 GHz, the microwave signal with its power larger than -17.94 dBm $(\gamma = 1)$ or -27.72 dBm $(\gamma = 0.8)$ can be measured under the noise background if the half-wave voltage of the Mach–Zehnder modulator is 6 V. These data can also be used to illustrate why a wider measurement range is ensured by a reduced relative peak-to-notch contrast ratio with which the transmission response would provide a larger power margin for a large range to suppress the background noise.

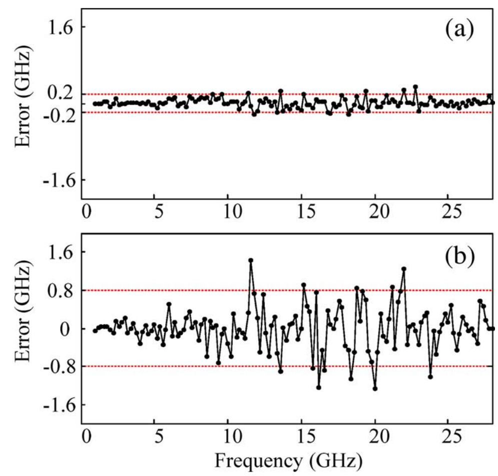

Fig. 11. Simulated error distributions under different noise backgrounds. (a) $\mathrm{SNR} = 16.5\mathrm{dB}$. (b) $\mathrm{SNR} = 11\mathrm{dB}$.

Note that the measurement error in the discussion above is set at ± 0.2 GHz or 5%, which is similar to the error (from tens to hundreds of megahertz) in the reported photonics-based approaches [4], [7], [9]–[12]. Compared to the measurement error of a currently available electronic spectrum analyzer, the measurement error is large. Like other photonics-based approaches, however, this approach here is proposed to realize a near real-time, wideband frequency measurement, which is a key feature that is required for applications where the main task is to monitor in real time the microwave frequency in a large bandwidth, while the resolution is not of the major concern. On the other hand, the proposed approach can be improved to have a much higher accuracy if the system is implemented using integrated photonic circuits, in which the complementary filter pair will have a better accuracy and stability.

V. Conclusion

In conclusion, we have proposed an approach for microwave frequency measurement by monitoring the optical powers using a complementary optical filter pair. Thanks to the complementary nature of the optical filters, a fixed relationship between the microwave frequency and the output powers was established, which enabled the estimation of the microwave frequency by simply monitoring the optical powers. A key advantage of the proposed approach is that the system is not sensitive to the optical power fluctuations since only a single light source was employed, which was eliminated in the expression for microwave frequency calculation. In addition, the entire system was significantly simplified since only a light source was used, which makes the alignment of the optical carrier with the central frequency of the complementary filter pair greatly simplified. To improve the measurement range, we proposed to use a complementary filter pair with spectral responses having a reduced relative peak-to-notch contrast ratio. In addition, the use of a filter pair with a smaller relative peak-to-notch contrast ratio would improve the SNR for microwave frequencies located at or close to the minimum transmission points of the spectral responses, which again increases the measurement range. The short- and long-term stability of the proposed system were also investigated. Potential solutions to improve the long-term stability were also proposed.

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