# An Approach to the Measurement of Microwave Frequency Based on Optical Power Monitoring

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***Abstract*—A novel approach to the measurement of microwave frequency based on optical power monitoring is proposed and demonstrated. The microwave signal with its frequency to be measured is modulated on two optical carriers with their wavelengths set at one peak and one valley of the spectral response of a sinusoidal filter. The modulation is performed by a Mach–Zehnder modulator that is biased to suppress the optical carriers. A mathematical expression relating the optical powers from the two wavelength channels and the microwave frequency to be measured is developed. By simply monitoring the optical powers at the outputs of the two wavelength channels, the microwave frequency can be evaluated. A proof-of-concept experiment is implemented. Frequency measurement with good accuracy for microwave signals at different power levels is realized.**

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

## I. INTRODUCTION

PHOTONICS techniques have been considered an important alternative to facilitate the generation, distribution, control, and processing of microwave signals for radar and other electronic warfare applications thanks to the numerous advantages offered by photonics, such as high bandwidth, light weight, low loss, and immunity to electromagnetic interference [1]–[3]. For defense applications, it is often required that a warfare system has the capability in estimating the carrier frequency of an unknown input signal over a large spectral range. In the past, channelizers and scanning receivers implemented based on photonics techniques have been demonstrated to achieve this function [4]–[6]. Microwave photonic channelizers realized based on parallel phase-shifted fiber Bragg gratings (FBGs) [4], or based on an integrated optical FBG Fabry–Pérot (F-P) and integrated hybrid Fresnel lens system [5], have been proposed for microwave frequency measurement and spectrum analysis. In [6], a scanning receiver using an F-P etalon was proposed for the estimation of the microwave frequency. Recently, a photonic technique for microwave frequency measurement was proposed [7]. The frequency measurement was realized by comparing the powers of two optical carriers that carry the microwave signal with double-sideband modulation that are propagating through a dispersive medium with different dispersion-induced power penalties.

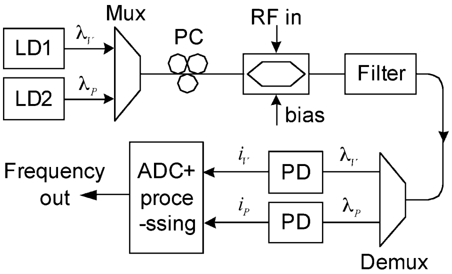

Fig. 1. Schematic diagram of the proposed approach for microwave frequency measurement.

In this letter, we propose and demonstrate a novel approach for microwave frequency measurement based on optical power monitoring. In the proposed approach, a microwave signal with unknown frequency is modulated on two optical carriers with their wavelengths set at one peak and one valley of the spectral response of a sinusoidal filter. The modulation is performed by a Mach–Zehnder modulator (MZM) that is biased to suppress the optical carriers. The frequency of the microwave signal is estimated by monitoring and comparing the optical powers at the outputs of the two wavelength channels. Since only dc optical powers are measured, the proposed system is easier to implement by using low-frequency components at a lower cost. A proof-of-concept experiment is performed, which verifies the feasibility of the approach.

## II. OPERATION PRINCIPLE

The schematic diagram of the proposed approach is shown in Fig. 1. Two optical carriers from two laser diodes (LDs) are combined at a multiplexer and sent to the MZM through a polarization controller (PC). The MZM is properly biased such that the optical carriers at the output of the MZM are completely suppressed. An optical filter with a sinusoidal spectral response is placed at the output of the MZM. The wavelengths of the two optical carriers are set at one peak and one valley of the filter spectral response. The carrier-suppressed optical signals are demultiplexed, with the optical powers measured by two low-frequency photodetectors (PDs). The dc currents from the PDs are digitized and compared in a data processing unit; the comparison between the two dc currents is used to estimate the frequency of the input microwave signal.

As shown in Fig. 2, the wavelengths of the two optical carriers are set at one valley ($\lambda_V$) and one peak ($\lambda_P$) of the spectral response of the sinusoidal filter. We assume that the powers

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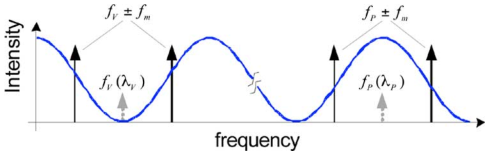


Fig. 2. Operation principle of the proposed technique. The wavelengths of the two optical carriers are selected such that one carrier is located at one peak and the other is located at the valley of the spectral response.

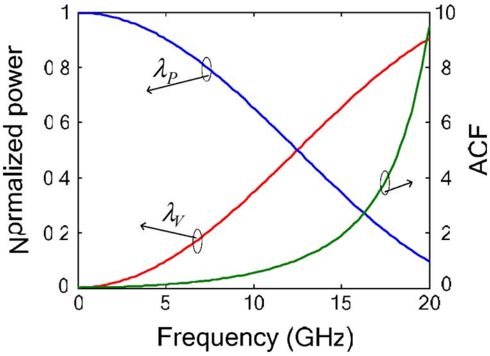


Fig. 3. Calculated results of the dependence of the detected optical power and the ACF on the input microwave frequency.

of the two optical carriers are the same, denoted by $P_0$. For small signal modulation, higher order optical sidebands can be ignored. Since the optical carriers are suppressed in the modulation, the detected optical power of each wavelength channel is just the optical powers of the two ±1st-order sidebands. The detected optical powers $P_V$ and $P_P$ of the channels $\lambda_V$ and $\lambda_P$ can be, respectively, written as

$$P_V = P_0[J_1(m)]^2 \left[1 - \cos\left(2\pi \frac{f_m}{\mathrm{FSR}}\right)\right] \tag{1}$$

and

$$P_P = P_0[J_1(m)]^2 \left[1 + \cos\left(2\pi \frac{f_m}{\mathrm{FSR}}\right)\right] \tag{2}$$

where $m$ is the modulation index which is related to the input microwave power, $f_m$ is the microwave frequency, $J_1(\cdot)$ is the Bessel function of the first kind of order 1, and FSR is the free spectral range of the sinusoidal filter. The ac components resulted from the beating between the ±1st-order sidebands are excluded in (1) and (2), since the low-frequency PDs employed in the system only respond to the dc components. The ratio between the two detected powers, referred to as the amplitude comparison function (ACF), can be expressed as

$$\begin{aligned}\mathrm{ACF} = \frac{P_V}{P_P} &= \frac{1 - \cos(2\pi f_m/\mathrm{FSR})}{1 + \cos(2\pi f_m/\mathrm{FSR})} \\ &= \left[\tan\left(\pi \frac{f_m}{\mathrm{FSR}}\right)\right]^2. \end{aligned} \tag{3}$$

Note that the ACF is not dependent on the input optical power and the microwave modulation index. Fig. 3 shows the dependence of the detected optical power and the ACF on the microwave frequency, where the FSR of the filter is set as 50 GHz. The ACF is increasing monotonically when the frequency is increased from 0 to FSR/2 (25 GHz in this case). Therefore, based on the value of the ACF, we can estimate the frequency of the input microwave signal. According to (3), the microwave frequency can be estimated based on the measured ACF value, $f_m = (\mathrm{FSR}/\pi) \cdot \tan^{-1}(\sqrt{\mathrm{ACF}})$.

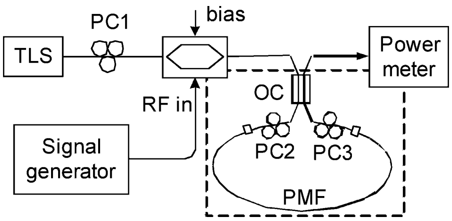


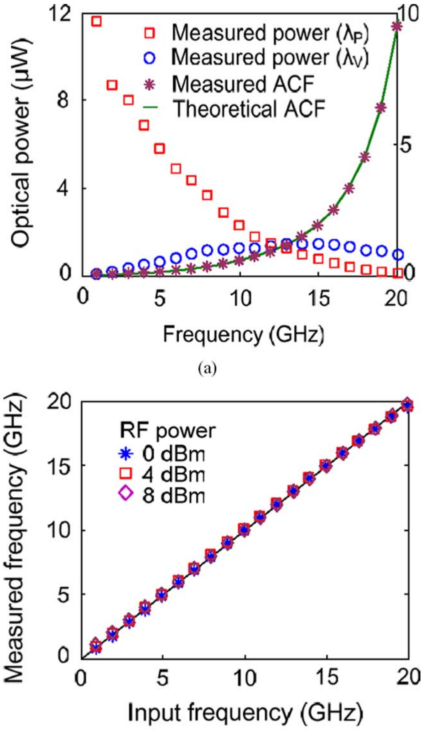
Fig. 4. Experimental setup (OC: optical coupler).

## III. EXPERIMENTAL RESULTS AND DISCUSSION

A proof-of-concept experiment with the setup shown in Fig. 4 is implemented. A two-tap Sagnac-loop filer (SLF) is used to act as the sinusoidal filter. The SLF, consisting of a length of polarization-maintaining fiber (PMF) and two PCs, has a sinusoidal spectral response with an FSR determined by the length and the birefringence of the PMF [8]. The transfer function of the SLF is given by $H_{\mathrm{SLF}}(f) = 1 + \cos(2\pi f \tau)$, where $f$ is the optical frequency and $\tau$ is the time delay difference introduced due to the birefringence of the PMF. The SLF has a sinusoidal spectral response with an FSR of 50 GHz (~0.4 nm at the 1550-nm band). A microwave signal with a frequency tunable from 1 to 20 GHz is generated by a signal generator (Agilent 8254A). We record the detected optical powers by an optical power meter (HP 81630) at the valley and the peak wavelengths by tuning the wavelength of the tunable laser source (TLS) (Anritsu MG9638A). The output power of the TLS is fixed at 12 dBm. In the experiment, we use a LabView program to control the TLS and the signal generator, and also to read the data from the optical power meter through a GPIB interface. The data measurement process can be completed within a short time duration of several tens of milliseconds.

Fig. 5(a) shows one set of the experimental results, where the input microwave power is set at 0 dBm. As can be seen the measured ACF matches well with the calculated ACF. By comparing Fig. 5(a) with Fig. 3, it is found that the curves of the received optical power are largely different from the calculated curve. The optical powers detected at high frequency are lower than those calculated. It is due to the fact that the radio-frequency half-wave voltage ($V_\pi$) of the MZM is getting higher when the microwave frequency is increased. We know that the modulation index $m$ is related to $V_\pi$ by $m = \pi V_s / V_\pi$, where $V_s$ is the voltage of the microwave signal. However, since the ACF is independent of the microwave modulation index, the variation of the half-wave voltage of the MZM should have no impact on the final ACF result. From Fig. 5(a), we can see the experimental ACF values agree well with the predicted values.

We have obtained three sets of data under input microwave power levels at 0, 4, and 8 dBm. Fig. 5(b) shows the measured frequencies obtained from the three set of data as well as the actual frequencies. The errors between the measured values and the actual frequency values are shown in Fig. 6. It is seen that the errors are basically limited within ±0.2 GHz. This resolution is acceptable since a rough estimation of the frequency realized by



(a)

(b)

Fig. 5. (a) Measured optical powers and the ACF values. (b) Estimated frequencies based on the measured ACF values. Solid line is the actual frequency.

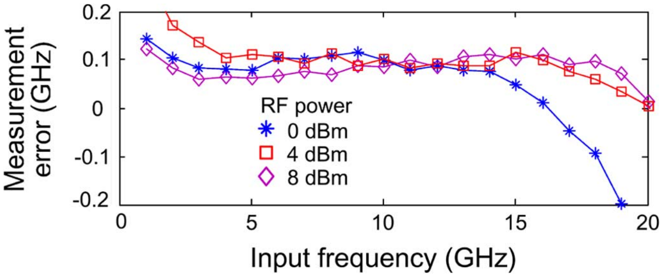


Fig. 6. Measurement errors for the microwave signals at different power levels.

this type of receiver is sufficient for the complexity reduction in other specialized receivers within the overall system [7].

The measurement accuracy is affected mainly by two error sources. The first one comes from the bias drift of the MZM which leads to the limited suppression of the optical carriers. Residual optical carrier powers would lead to the received optical powers deviating from the theoretical values, especially when the sideband optical powers are low (corresponding to the microwave frequencies close to dc and FSR/2 of the filter response, as can be seen from Fig. 6). To improve the performance of the optical carrier suppression, techniques for an accurate control of the bias voltage should be used [9]. The second error source is the misalignment of the wavelengths of the optical carriers with the valley and peak of the frequency response of the sinusoidal filter due to the wavelength drifts of the laser sources and the shift of the filter spectral response. In our proof-of-concept experiment, an SLF was employed as the sinusoidal filter. The major problem associated with the use of a fiber-based SLF is its high sensitivity to environmental changes, which may affect the stability of the entire system. A theoretical analysis on the impact of the temperature stability of the SLF on the measurement accuracy is performed. For a PM fiber with a temperature-dependent birefringence coefficient of $d\Delta n/dT = -7 \times 10^{-8}$ used in the SLF, a measurement error is calculated to be less than $5\%$ for a frequency range from 5 to 20 GHz if the temperature stability is controlled within $\pm 0.12$ °C. This conclusion is confirmed by an experiment. If a photonic crystal PM fiber with a reduced temperature sensitivity of $d\Delta n/dT = -2 \times 10^{-9}/K$ is used in the SLF [10], to achieve the same measurement accuracy, the temperature stability is reduced to $\pm 2$ °C.

## IV. CONCLUSION

A novel approach to the measurement of microwave frequency based on optical power monitoring was proposed and demonstrated. Since the approach was based on the optical power monitoring, no microwave components except an MZM were used in the system, which leads to a reduced complexity and cost. A proof-of-concept experiment was performed to demonstrate the feasibility of the proposed approach. Good agreement between the measured and the actual frequencies was reached. The approach provides an important alternative for the measurement of microwave frequency for electronic warfare applications.

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