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MICROWAVE FREQUENCY MEASUREMENT BASED ON PHASE MODULATION TO INTENSITY MODULATION CONVERSION USING FIBER BRAGG GRATING

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Abstract—A simple photonic technique for instantaneous microwave frequency measurement using an optical phase modulator and a fiber Bragg grating (FBG) is proposed and investigated. The FBG acts as tilt filters to offer different slopes of suppression for the optical carrier and the two sidebands when wavelengths are located at different positions of the FBG. A fixed relationship between the microwave frequencies and microwave powers is established. The microwave frequency can be estimated by measuring the microwave power differences. A measurement resolution of ±0.22 GHz over a 15 GHz measurement bandwidth is achieved. Experiments are performed to verify the effectiveness of the proposed approach.

1. INTRODUCTION

Microwave frequency measurement techniques have attracted significant interest for their important applications in wireless communication networks, radar and electronic warfare systems [1–4]. Conventional techniques are usually limited in bandwidth and suffer from electromagnetic interference [5, 6]. Thanks to the advantages such as high bandwidth and low loss offered by modern photonics [7–9], a few approaches have been proposed for instantaneous microwave frequency measurement based on frequency-to-power mapping [10–16]. In [12], the frequency of a microwave signal was estimated by measuring the microwave powers at the outputs of the two photodetectors (PDs), with the microwave signal carried by two different optical wavelengths

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that experience different power fading function. In [13], an approach based on an optical phase modulator was demonstrated.

In this paper, a photonic technique for measuring the frequency of a microwave signal using an optical phase modulator and a FBG is proposed. Recently FBG has attracted considerable attentions due to its diversity of reflection spectrum [17–20]. In the proposed approach, a microwave signal with unknown frequency is modulated on two optical carriers with their wavelengths set at two different positions of the spectral response of an FBG. Optical phase modulation (PM) is converted to intensity modulation (IM) by reflecting the phase-modulated light at the slope of the FBG reflection spectrum. Since the obtained RF powers on the microwave frequency at the two positions are different, the microwave power ratio can be used to determine the microwave frequency. The well-packaged athermal FBG is used in the proposed system, which leads to be insensitive to the temperature fluctuation. The advantage of employing a phase modulator is that it does not need to be biased and has smaller insertion loss compared with common intensity modulation schematics. In addition, the measured microwave frequency is independent of the power of the optical source, which makes the frequency measurement insensitive to the power fluctuations. The proposed technique is experimentally demonstrated, and a good agreement is achieved.

2. PRINCIPLE

Under small signal condition, the output optical field $E(t)$ of a phase modulator driven by a single frequency microwave signal can be written as [21]

$$\begin{aligned} E(t) \;=\; & A_0\cos(w_c t) + A_1\cos[(w_c + w_m)t + \pi/2] \\ & -A_{-1}\cos[(w_c - w_m)t - \pi/2] \end{aligned} \tag{1}$$

where w_c is the angular frequency of the optical carrier, w_m is the modulating angular frequency, A_0 and A_1, A_{-1} are the amplitudes of the optical carrier and two sidebands, respectively. So the current after photodiode detection can be expressed as

$$\begin{aligned} i(t) \;\propto\; & |E(t)|^2 = A_0^2 + A_1^2 + A_{-1}^2 + A_0A_{-1}\cos[w_m t + \pi/2] \\ & -A_0A_1\cos[w_m t + \pi/2] + A_1A_{-1}\cos[2w_m t + \pi] \end{aligned} \tag{2}$$

Then the received RF power at frequency f_m is

$$P_{rf} \propto A_0^2(A_{-1} - A_1)^2 \tag{3}$$

It is well-known that the phase-modulated signal cannot be directly detected by a PD. Optical phase modulation to intensity modulation

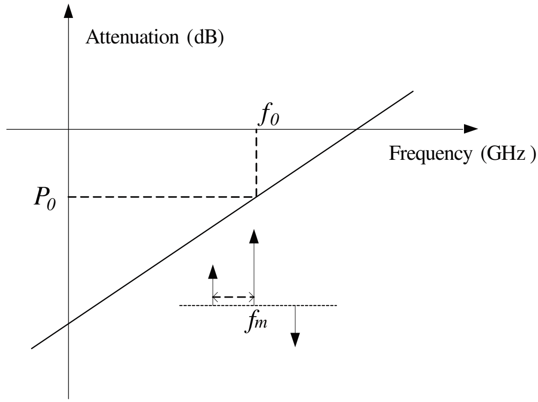

Figure 1. Block diagram of Characteristics of an external tilt filter.

(PM-IM) conversion can be realized if the amplitude-equality of the two first sidebands is broken, and this can be achieved by reflecting the phase-modulated light signal at the slope of an FBG, which serves as a tilt filter [22].

If an external filter has the first order approximation as illuminated in Fig. 1, its power attenuation is expressed as

$$P(f_m) = P(f_0) + \alpha f_m = P_0 + \alpha f_m \tag{4}$$

where P_0 is the attenuation of optical carrier power, f_m is the modulated sideband frequency, and α is the slope of the line in dB/GHz. The amplitudes of optical carrier and sidebands of the PM signals after this filter will be expressed as

$$\begin{aligned} A'_0 &= A_0 10^{P_0/20} \\ A'_{-1}(f_m) &= A_{-1}(f_m) 10^{(P_0-\alpha f_m)/20} \\ A'_1(f_m) &= A_1(f_m) 10^{(P_0+\alpha f_m)/20} \end{aligned} \tag{5}$$

So the received RF power after direct detection by a PD can be expressed as,

$$P_{rf} \propto 10^{P_0/10} \left[10^{(P_0+\alpha f_m)/20} - 10^{(P_0-\alpha f_m)/20}\right]^2 \tag{6}$$

In order to determine the microwave frequency, two different wavelengths are needed. The two wavelengths are located at different slopes of the tilt filter with α and β, respectively. Then we have the power ratio between the two wavelengths as

$$\gamma = \left[10^{\alpha f_m/20} - 10^{-\alpha f_m/20}\right]^2 \Big/ \left[10^{\beta f_m/20} - 10^{-\beta f_m/20}\right]^2 \tag{7}$$

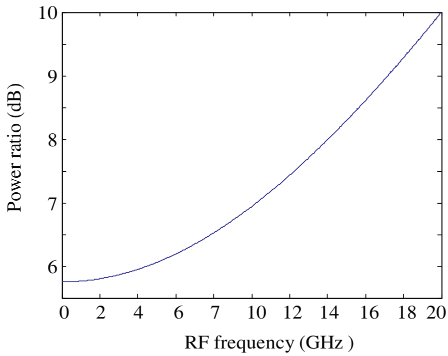

Figure 2. Block diagram of Simulation result of power ratio vs microwave frequency.

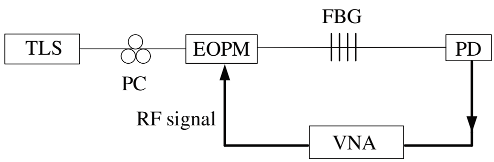

Figure 3. Experimental setup of the proposed approach for instantaneous microwave frequency measurement.

Figure 2 shows the simulation result of the proposed technique. $\alpha = 0.8$ and $\beta = 0.6$, and the measurement range f_m of 0 to 20 GHz. Since the simulation result is monotone, for a system with a given FBG, the microwave frequency can be estimated based on measuring the microwave powers at the output of the two optical wavelengths.

3. EXPERIMENT AND DISCUSSION

The block diagram of the proposed technique is shown in Fig. 3. A tunable laser source (Agilent 81940A) is employed as the optical carrier through a polarization controller (PC), the signal is modulated by the RF input signal *via* an electrooptical phase modulator (EOPM). This 20 GHz EOPM is based on the linear electro-optical effect of $LiNbO_3$ crystal, with a half voltage of 5 V. Then the phase-modulated optical signal is applied to an FBG, which functions in a transmission mode. This optical signal is fed to a high-speed PD, which has the sensitivity of 0.9 A/w and the maximum input optical power of 10 dBm. The RF response is measured by a vector network analyzer (Agilent 8720ET).

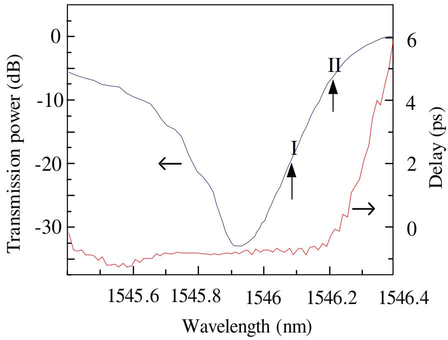

Figure 4. Transmission spectrum and dispersion characteristics of the chosen fiber Bragg grating.

Figure 4 shows the transmission spectrum of an FBG used with the center optical wavelength of 1545.92 nm. Full-width-half maximum (FWHM) of the FBG is about 0.25 nm, and its maximum insertion loss at center wavelength is 34 dB. In Fig. 4, I and II represent two different positions of the wavelengths at the slope of the FBG transmission spectrum, respectively.

In the experiment, two power distributions measured using the VNA, with the two wave-lengths set at 1546.08 nm and 1546.22 nm, respectively. We firstly measure the dependence of the received microwave power on the frequency when the carrier located at two positions. The calculated power ratio function can be viewed as a calibration process, which is shown in Fig. 5(a). The reason to choose this two wavelengths as the measuring points is to make sure that the difference between the two slopes is as large as possible. If the variation between slopes is relatively small, the monotone interval of the power ratio function could not be used due to the flatness in the response curve, which limits the measurement frequency range, and also increases the measure error. Then, we tune the frequency of the input microwave signal and record the measured frequency. The results are shown in Fig. 5(b) as circles. Fig. 5(c) is the measurement errors calculated by comparing the measured frequencies and the input frequencies. It can be seen that for a given measurement accuracy, say ± 0.22 GHz, the measurement range is $3 \sim 18$ GHz.

The dispersion parameter of the FBG is calculated using the measured reflection spectrum [23]. The dispersion of the FBG in the bandwidth is nearly a constant and low, while at the edges it becomes a little stronger. The dispersion of the FBG at II position is nearly 34 ps/nm, which has the same effect as a 2 km length fiber link with

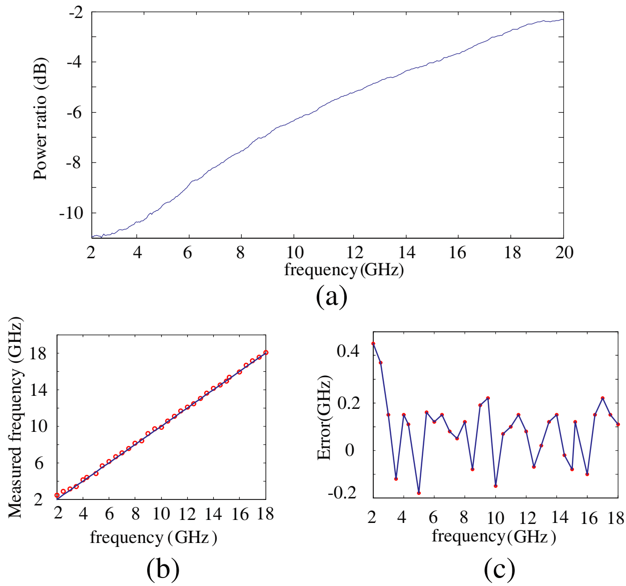

Figure 5. Experimental results. (a) Power ratio function; (b) Measured frequency; and (c) Measurement errors.

fiber dispersion constant $D = 17\,\mathrm{ps/nm\,km}$. So the received RF power after direct detection by a PD can be expressed as [22],

$$P_{rf} \propto \left(10^{(P_0+\alpha f_m)/20} + 10^{(P_0-\alpha f_m)/20}\right)^2 \sin^2\left(\pi\lambda_0^2 DLf_m^2/c\right) + \left(10^{(P_0+\alpha f_m)/20} - 10^{(P_0-\alpha f_m)/20}\right)^2 \cos^2\left(\pi\lambda_0^2 DLf_m^2/c\right) \quad (8)$$

where $\lambda_0 = c/f_0$ is the wavelength of optical carrier. The power ratio in Eq. (7) is changed as

$$\gamma = \left[\left(10^{\alpha f_m/20} + 10^{-\alpha f_m/20}\right)^2 \sin^2\left(\pi\lambda_0^2 DLf_m^2/c\right) + \left(10^{\alpha f_m/20} - 10^{-\alpha f_m/20}\right)^2 \cos^2\left(\pi\lambda_0^2 DLf_m^2/c\right)\right] \Big/ \left(10^{\beta f_m/20} - 10^{-\beta f_m/20}\right)^2 \quad (9)$$

In the experiment, $L = 2\,\mathrm{km}$, $\lambda_0 = 1546.22\,\mathrm{nm}$. The simulation result is still monotone, which is shown in Fig. 6. Thus the chromatic dispersion of the FBG will have little influence on the experimental results.

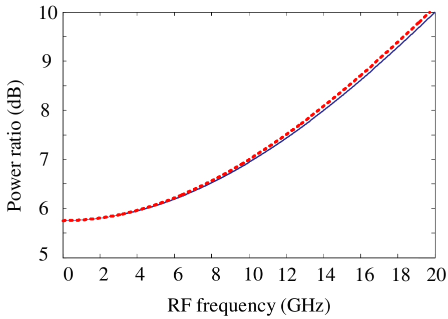

Figure 6. The simulation result considering the chromatic dispersion of the FBG.

The main measurement error is mainly caused from the system noise [11]. In addition, since FBGs can provide a great diversity of transmission spectra [24, 25], if two specifically FBGs are designed with different linearity slopes in the measured range, then only a single light source is employed. The system will not be sensitive to the optical power fluctuations and the entire system can be significantly simplified. And according to Eq. (7), the simulation result is still monotone when the measurement range f_m is $0 \sim 100\,\text{GHz}$, so it is feasible to obtain relatively large measurement range if the linear range is wide enough.

4. CONCLUSION

A novel technique for instantaneous microwave frequency measurement using an optical phase modulator and an FBG is proposed. The microwave frequency was calculated by measuring the microwave powers, due to a fixed relationship between the power ratio and the microwave frequency. The key significance of the proposed approach is the use of an FBG serving as tilt filters with different slopes at different positions. The entire system was significantly simplified and cost-effective since only an FBG was used. In addition, the use of optical phase modulator makes the system simpler for needing no biased and its smaller insertion loss. In addition, the measurement range can be highly improved with specifically designed FBGs, which is a key feature for wideband frequency measurement applications.

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