Instantaneous Microwave Frequency Measurement Using a Special Fiber Bragg Grating

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***Abstract*—A photonic approach to realizing instantaneous microwave frequency measurement based on frequency to optical power ratio mapping using a special fiber Bragg grating (FBG) is proposed and demonstrated. The special FBG is designed to have a spectral response with two slopes that are inversely proportional to optical frequency, which enables the realization of a linear power ratio function, leading to an increased measurement range and improved measurement accuracy. The FBG is fabricated and the incorporation of the FBG in a system for frequency measurement is experimented. Instantaneous microwave frequency measurement with a measurement range of 1–10 GHz and a measurement accuracy of ± 0.2 GHz under different input microwave power levels is realized.**

***Index Terms*—Fiber Bragg grating (FBG), instantaneous frequency measurement, microwave photonics.**

I. Introduction

FOR modern radar and other electronic warfare (EW) applications, it is required that a microwave receiver is able to measure the frequency of an intercepted microwave signal over a large bandwidth [1]. As the conventional electronic techniques are thought to be slow, limited in bandwidth and vulnerable to electromagnetic interference (EMI), numerous photonic approaches have been proposed and demonstrated to achieve instantaneous frequency measurement (IFM) of a single-frequency microwave signal based on the frequency to power mapping techniques [2]–[7].

In [2]–[5], the microwave frequency was estimated according to the ratio of two RF power-fading functions. The RF power fading can be easily achieved in an intensity- or phase-modulated dispersive fiber link. The main limitation of the technique is that high-speed photodiodes (PDs) are needed which may increase the system cost. On the other hand, the frequency of a microwave signal can also be measured by monitoring two optical powers that are obtained by passing the modulated optical signal through two optical filters with different spectral responses [6], [7]. Since optical power monitoring can be done using low-speed PDs, the cost of the system can be significantly reduced. However, the power ratio function (PRF) is nonlinear, which makes the system have a reduced measurement resolution at the frequencies where the slopes of the PRF are small [7]. Furthermore, measurement ambiguities would exist since the PRF is usually a non-monotone function.

In this letter, we propose and demonstrate a novel approach to realizing IFM based on optical power monitoring using a special fiber Bragg grating (FBG). The key component in the system is the special FBG which is designed to have a spectral response with two slopes that are inversely proportional to optical frequency. By monitoring the optical powers at the outputs of the FBG operating in both transmission and reflection, a linear relationship between the microwave frequency and the optical power ratio is achieved. Since only the optical powers are monitored, low-speed PDs are required, which reduces the cost of the system. A special FBG is designed and fabricated. The incorporation of the special FBG in the frequency measurement system is demonstrated. Instantaneous microwave frequency measurement with a measurement range of 1–10 GHz and a measurement accuracy of ± 0.2 GHz under different input microwave power levels is realized.

II. Principle

The schematic of the proposed system is shown in Fig. 1. A CW light wave from a laser diode (LD) is sent to a Mach–Zehnder modulator (MZM) through a polarization controller (PC). A microwave signal with its frequency to be measured is applied to the MZM via the RF port. The MZM is biased at the minimum transmission point (MITP) to suppress the optical carrier. The modulated optical signal is sent to an FBG via an optical circulator. The wavelength of the LD is aligned with the center wavelength of the FBG. The transmitted and the reflected optical signals from the FBG are monitored by two optical power meters (low-speed PDs). The dc currents detected by the two power meters, which are proportional to the transmitted and reflected average optical powers, are sent to a post processing unit to acquire their power ratio. The microwave frequency is estimated based on the value of the power ratio.

As shown in Fig. 2(a), the wavelength of the optical carrier is aligned with the center wavelength of the FBG. Assume the output optical power of the LD is P_0. Since the optical carrier (f_c) is suppressed in the modulation process, under a small signal modulation condition, the detected optical power is equal

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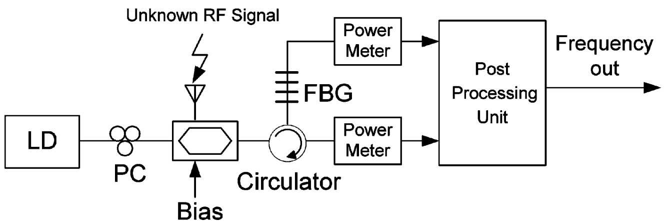

Fig. 1. Schematic of the proposed system for instantaneous microwave frequency measurement.

to the powers of the two first-order sidebands, which are both equal to $P_0 J_1^2(\beta)$ before passing the FBG, where $\beta = \pi V_m / V_\pi$ is the modulation index, V_m is the amplitude voltage of the microwave signal, V_π is the half-wave voltage of the MZM and $J_1(\cdot)$ denotes the first-order Bessel function of the first kind. To achieve a linear PRF with improved resolution, the shape of the reflection spectrum of the FBG is designed such that the two slopes are inversely proportional to optical frequency. Thus, the frequency responses of the reflection and transmission of the FBG are designed to be

$$T(f) = \frac{k|f - f_c|}{1 + k|f - f_c|} \tag{1}$$

$$R(f) = 1 - T(f) = \frac{1}{1 + k|f - f_c|} \tag{2}$$

where k is the designed slope of the PRF, which is a constant and can be used to design the spectral response of the FBG. Therefore, the detected transmitted and reflected optical powers with respect to the microwave frequency to be measured, f_m, can be expressed as

$$\begin{aligned} P_T &= P_0 J_1^2(\beta)[T(f_c + f_m) + T(f_c - f_m)] \\ &= 2P_0 J_1^2(\beta) \frac{k f_m}{1 + k f_m} \end{aligned} \tag{3}$$

$$\begin{aligned} P_R &= P_0 J_1^2(\beta)[R(f_c + f_m) + R(f_c - f_m)] \\ &= 2P_0 J_1^2(\beta) \frac{1}{1 + k f_m}. \end{aligned} \tag{4}$$

Based on (3) and (4), we can obtain the power ratio of the transmitted and reflected optical signals

$$r = \frac{P_T}{P_R} = k f_m. \tag{5}$$

As can be seen from (5), the power ratio is linearly proportional to the microwave frequency and is independent of the modulation index or the input optical power. To further demonstrate the principle, a calculation is performed using Matlab to show the frequency response of the special FBG and the dependence of the detected optical powers and the power ratio on the microwave frequency. In the calculation, k is set at 0.4/GHz, P_0 is set at 10 dBm and β is set at 0.15. Fig. 2(a) shows the transmission and reflection frequency responses of the designed FBG based on (1) and (2). Fig. 2(b) shows the dependence of the transmitted power P_T, the reflected power P_R and the power ratio r on the microwave frequency f_m based on (3)–(5). P_T and P_R are normalized to $2P_0 J_1^2(\beta)$. As can be seen, a linear PRF is achieved and the microwave frequency can be deduced

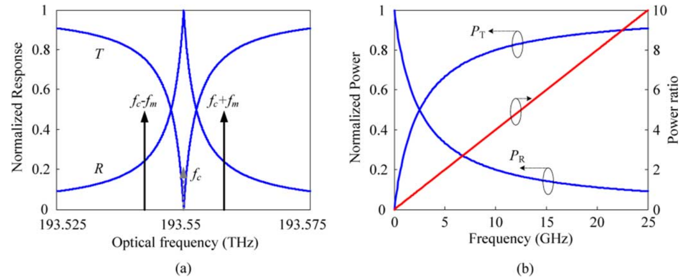

Fig. 2. Calculated results. (a) Frequency responses of the special FBG with two slopes that are inversely proportional to optical frequency. (b) Dependence of the detected optical powers and the power ratio on the microwave frequency.

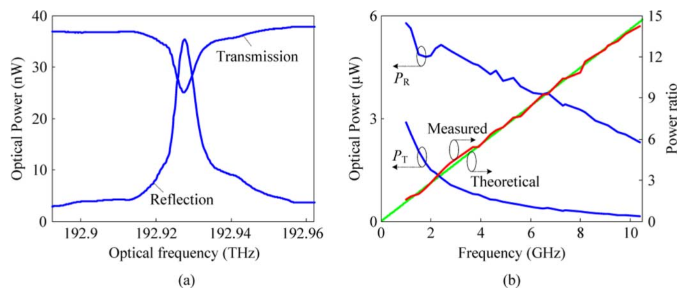

Fig. 3. (a) Transmission and reflection frequency responses of the fabricated FBG. (b) The averaged detected optical power and the theoretical and measured PRF with 4 dBm microwave power.

from the power ratio value by calculating $f_m = r/k$ without ambiguity.

III. Experimental Results

An experiment based on the setup shown in Fig. 1 is performed. An FBG with a spectral response having two slopes that are inversely proportional to optical frequency is fabricated. The required grating profile is designed using the well-known discrete layer-peeling (DLP) algorithm. The designed FBG is then fabricated in a hydrogen-loaded single-mode fiber by a frequency-doubled argon-ion laser (Coherent FreD 300 C) operating at 244 nm using a 15 cm long uniform phase mask. The apodization is achieved by controlling the UV laser beam scanning velocity while maintaining a constant laser output power. The transmission and reflection frequency responses of the fabricated FBG are shown in Fig. 3(a). The ripples in the FBG frequency responses are mainly from the deviations of the refractive index change profile from the designed function, which are resulted from 1) the power variations of the argon-ion laser, 2) the wobbling of the translation stages, and 3) the errors in the phase mask [8]. The output power of the tunable laser source (YOKOGAWA AQ2201) is fixed at 12 dBm and the wavelength is tuned to match the center wavelength of the FBG. The optical carrier is modulated by a microwave signal from a signal generator (Agilent E8254A) at an MZM (20 GHz bandwidth, JDS-Uniphase) which is biased at the MITP. The optical powers are recorded by an optical power meter (Agilent 81630B). Both the signal generator and the power meter are controlled by a C++ program through a GPIB interface, which ensures a fast and accurate measurement.

Fig. 3(b) shows the experimental results, in which the power of the microwave signal is set at 4 dBm. As can be seen, a linear

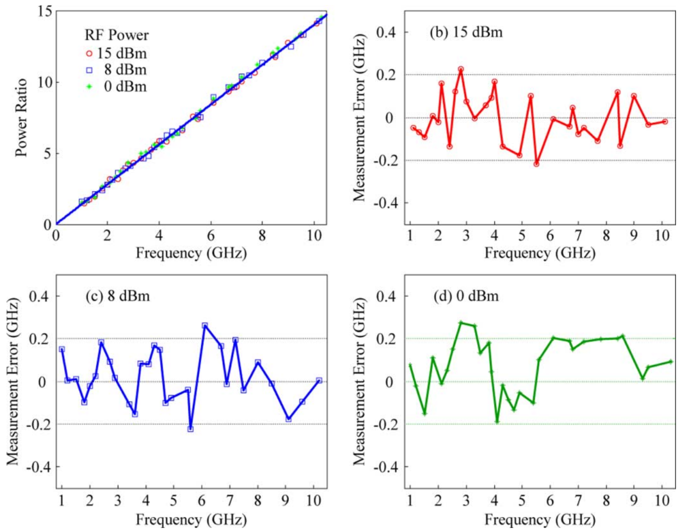

Fig. 4. (a) Measured power ratios for different input microwave powers. (b)-(d) Measurement errors at four power levels: 15, 8, and 0 dBm.

power ratio in a frequency range of 1–10 GHz is obtained. Some fluctuations are observed in the PRF, which are resulted from the ripples in the frequency responses of the FBG.

To verify the independence of the frequency measurement with the input microwave power, as indicated in (5), we adjust the input microwave powers at three different levels: 15 dBm, 8 dBm, and 0 dBm. Fig. 4(a) shows the power ratios for these three input microwave power levels. As can be seen, the PRFs are all linearly proportional to the microwave frequency. Fig. 4(b)-(d) shows the measurement errors for these three different input microwave powers. It is shown that measurement errors of about ±0.2 GHz in a frequency range of 1–10 GHz are achieved.

IV. Discussion and Conclusion

In [7], a similar schematic as shown in Fig. 1 was employed to realize IFM in which a quasi-Gaussian-shaped FBG was utilized. The key improvement here is the linear PRF, realized using a special FBG, which can improve the measurement accuracy, especially at low frequencies. The measurement errors in Fig. 4 are larger than those in [7] even at low frequencies. The reason is that the FBG in [7] was much easier to fabricate due to the less sharp slopes of the frequency response, which lead to smaller spectral ripples. In the proposed approach, since the FBG has sharp slopes, the fabrication is more complicated with larger spectral ripples. To have a better understanding of the impact of the spectral ripples on the measurement accuracy, a further calculation is performed. Assume the fabrication errors at f_c+f_m and f_c-f_m in the reflection frequency response $R(f)$ are δ, then the new power ratio is given by

$$r' = \frac{1-(1-\delta)\frac{1}{1+kf_m}}{(1-\delta)\frac{1}{1+kf_m}}. \tag{6}$$

The measurement error at f_m is given by

$$f_{err} = \frac{r'}{k} - f_m = \frac{1-(1-\delta)\frac{1}{1+kf_m}}{k(1-\delta)\frac{1}{1+kf_m}} - f_m = \frac{\delta}{1-\delta}\cdot\left(\frac{1}{k}+f_m\right). \tag{7}$$

(7) can also be used to estimate the needed accuracy of the reflection and transmission frequency responses for a given measurement accuracy. For example, when $k = 0.4$/GHz and the measurement accuracy is ±0.2 GHz, δ should be smaller than 1.6% for a measurement range of 1–10 GHz.

In conclusion, an approach to the instantaneous measurement of a microwave frequency based on optical power monitoring using a special FBG was proposed and experimentally demonstrated. The fundamental concept was to design a special FBG by which a linear PRF with a large slope could be achieved with a uniform resolution. An experiment was implemented, in which a linear PRF was achieved. Measurement errors of ±0.2 GHz in a frequency range of 1–10 GHz were obtained for different input microwave power levels. The influence of the ripples on the reflection and transmission frequency responses was also analyzed.

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