Measurement of Microwave Frequency Using a Monolithically Integrated Scannable Echelle Diffractive Grating

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***Abstract*—A novel approach to the measurement of microwave signal frequency is studied and demonstrated. The approach is based on a monolithically integrated echelle diffractive grating (EDG). The microwave signal is converted to an optical signal of two sidebands using an optical carrier and a Mach–Zehnder modulator. One of the sidebands is then filtered out by a fiber Bragg grating, while the other sideband is characterized by an EDG-based interrogator. Due to the better than 1-pm interrogation resolution of this interrogator, the center wavelength of the sideband tested is capable of being accurately measured. Combining this data with the wavelength of the optical carrier used, the frequency of the microwave signal can be calculated. The results obtained are found to be in good agreement with those of the microwave signals.**

***Index Terms*—Echelle diffractive grating (EDG), fiber Bragg grating (FBG), frequency measurement, microwave photonics.**

I. Introduction

PHOTONIC techniques have been well documented for generating, distributing, controlling, and processing microwave signals for radar and other electronic warfare (EW) applications due to their numerous advantages, such as high bandwidth, low loss, light weight, and immunity to electromagnetic interference [1]. One of the basic requirements for EW applications is to estimate the frequency of an unknown microwave signal over a large bandwidth. Conventional microwave architectures usually make the measurement systems very bulky and costly. Thus, considerable effort has been devoted to develop novel techniques for microwave frequency measurements using photonic techniques, such as Fabry–Pérot etalon-based scanning receiver [2], integrated hybrid Fresnel lens systems [3], parallel phase-shifted fiber Bragg grating (FBG)-based photonic channelizers [4], and optical power monitoring of two optical carriers with power penalties introduced by different dispersions [5].

In this letter, a novel approach with multimicrowave frequency measurement capability is proposed. The approach is based on a monolithically integrated echelle diffractive grating (EDG) [6] interrogator having 15 measurement channels. One of those channels is used to demonstrate the feasibility of the proposed approach. Some initial experimental results are also presented in this letter.

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II. Theory

In modulating a microwave signal with unknown frequency on an optical carrier, two sidebands in the optical domain can be generated while the optical carrier can be suppressed by properly setting the bias of a Mach–Zehnder modulator (MZM) [7]. If an FBG is introduced as a notch filter [8] to filter out one of the two sidebands, the center wavelength λ_S of the remaining sideband can be related to the frequency of the microwave signal f by

$$f = |\upsilon_C - \upsilon_S| = c\left|\left(\frac{1}{\lambda_C} - \frac{1}{\lambda_S}\right)\right| \tag{1}$$

where υ_C and υ_S are the frequencies of the suppressed optical carrier and the remaining sideband, respectively, c is the light speed in vacuum and λ_C is the wavelength of the suppressed optical carrier. Therefore, by knowing the wavelength of the sideband passing through the FBG filter, it is possible to determine the frequency of the microwave signal. Now, considering the EDG-based interrogator and according to [9], the transmission spectrum of the jth channel of an EDG interrogator is given by

$$I_j = I_0 \exp\left[\frac{-4\ln 2(\lambda - \lambda_{Ej})^2}{\Delta\lambda_{Ej}^2}\right] \tag{2}$$

where I_0, λ_{Ej}, and $\Delta\lambda_{Ej}$ are the peak transmittance, center wavelength, and full-width at half-maximum of the jth output channel of an EDG. In this study, it is assumed that the transmission wavelength of the jth EDG channel is shifting monotonically with the EDG interrogator chip temperature as follows:

$$\lambda_{\mathrm{EDG}j} = M(T) + \lambda_0 \tag{3}$$

where $M(T)$ is the monotonic temperature dependent function, T is the EDG chip temperature, and λ_0 is a constant.

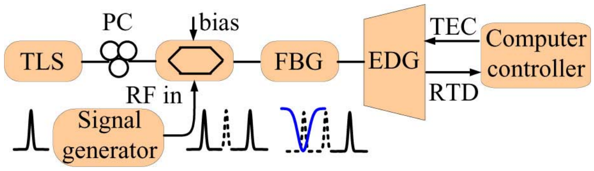

Fig. 1. Experimental setup of the proposed approach.

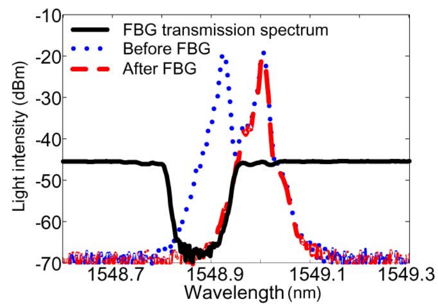

Fig. 2. Spectra of the FBG and the sidebands before and after the FBG with 5-GHz microwave signal applied on the MZM.

It is further assumed that the light intensity detected by the jth channel of the EDG is mainly from the sideband under measurement, while the contributions from the filtered out sideband and suppressed optical carrier are very small and can be neglected. This assumption can be realized by properly designing the FBG spectrum and setting the MZM bias. Then, based on the analyses presented in [9], the detected light intensity of the jth channel of the EDG will reach the maximum value when $\lambda_{\mathrm{EDG}j}$ reaches λ_S by tuning the EDG chip temperature. Therefore, by measuring the EDG chip temperature corresponding to the maximum light intensity output of channel j, the center wavelength of the sideband passing through the FBG filter can be determined using (3), while the frequency of the microwave signals can be calculated using (1) and (3).

III. Experimental Setup and Result

A proof-of-concept experiment with the setup illustrated in Fig. 1 is carried out to demonstrate the feasibility of the proposed approach.

The light signal from the tunable laser source (TLS) is used as the optical carrier and modulated by an MZM. By properly setting the MZM bias, the optical carrier is suppressed and two sidebands are generated, one of which is filtered out by the FBG notch filter as shown in Fig. 2, while the remaining sideband is characterized by an EDG-based interrogator. This interrogator, developed based on a monolithically integrated InGaAsP–InP chip consists, as detailed in [9], of a 1×15 EDG demultiplexer, an array of photodetectors (PDs), a thermal electric cooler (TEC), and a resistance temperature detector (RTD). The TEC and RTD are integrated in the chip for the purpose of adjusting and monitoring the EDG chip temperature. However, to improve the response speed of the interrogator, a different temperature control technique from the one used in [9] is employed in this work.

Fig. 3 shows the mapping relationship between the RTD readout and the wavelength by tuning an Agilent TLS (81640B) with a step of 5 pm. Considering that the center wavelength of the FBG is 1548.858 nm (shown in Fig. 2) and to simplify the data processing, the center wavelength of the optical carrier is selected to be 1548.964 nm and a 0.5-nm linear range is applied in this experiment. The linear coefficient in this selected linear region is measured as 84.4 pm/°C. Since the temperature reading resolution of the RTD used is 0.01 °C, a better than 1-pm wavelength interrogation resolution can be achieved.

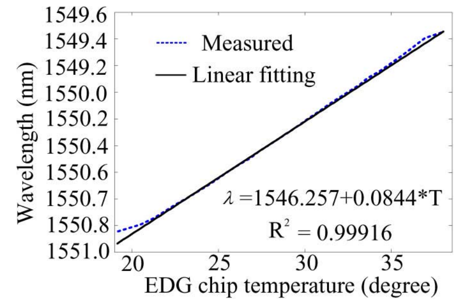

Fig. 3. Temperature dependence of the transmission wavelength.

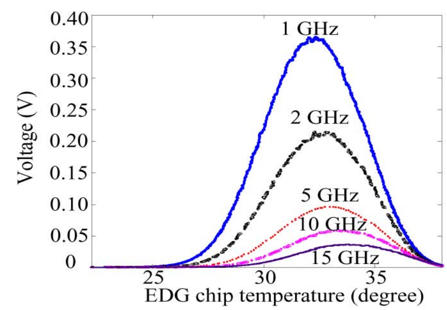

Fig. 4. Samples of the sideband shift measured by the EDG-based interrogator.

The power of the input microwave signal is set as 5 dBm and the scanning frequency is from 0 to 15 GHz with a step of 1 GHz. Fig. 4 shows the selected sideband spectra with respect to the EDG chip temperature under different microwave frequencies applied to the MZM. The optical carrier wavelength used in this experiment is selected slightly larger than the optimal number. Thus, the FBG cannot completely filter out the left sideband when lower microwave frequencies are applied. With the increase of the input microwave frequency, the left sideband shifts into the dip of the FBG spectrum as shown in Fig. 2. Hence, the contribution of its residual to the detected light intensity and the measured spectrum is decreasing, which results in the lowering of the power intensity and the narrowing of the bandwidth. This effect can be overcome by properly selecting the optical carrier wavelength.

By applying the above discussed process, the EDG chip temperatures representing the maximum value of detected light intensity and the corresponding center wavelengths of the remaining sideband under different input microwave frequencies are obtained and the results are shown in Fig. 5.

By substituting the above obtained wavelengths and the optical carrier wavelength in (1), the frequencies of the microwave signals can be obtained. The experimental results are correlated to the actual microwave frequencies and their relation is shown in Fig. 6.

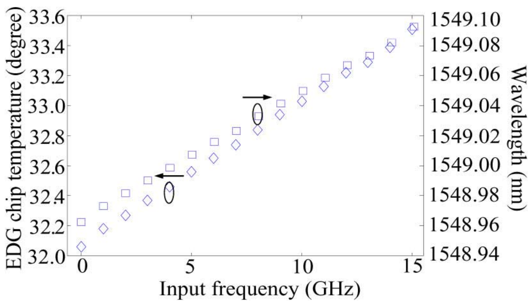

Fig. 5. Measured EDG chip temperatures and the corresponding wavelengths with different input microwave frequencies.

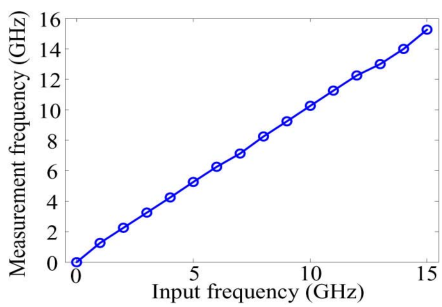

Fig. 6. Correlations of the measured and the actual frequencies.

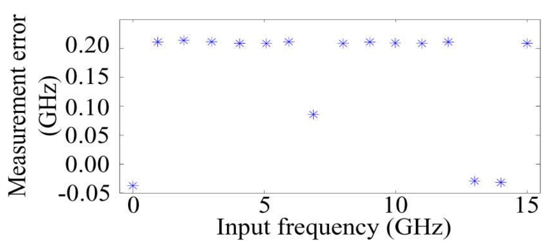

Fig. 7. Measurement errors.

Ideally, those two sets of values are equal. For this proof-of-concept work (as shown in Fig. 7), we find the measurement variation is mainly around 0.2 GHz from the one-to-one relationship, which accords well to the measurement accuracy of 10 pm in [9]. This accuracy level is also comparable with those reported in the literature [2]–[5]. The variations are believed to be attributed to two major error sources. The first error source is from the Gaussian spectra of the EDG interrogator. In a theoretically ideal case, the spectral function of the EDG transmission channels, implemented in the spectrum scanning, should be mathematically a Dirac delta function with an infinite height and a unity area. As discussed in [9], an EDG with a relatively smaller bandwidth is preferable to perform better spectrum scanning and yield better measurement accuracy. However, the EDG interrogator used has a 3-dB bandwidth of 0.4 nm, which would contribute to the measurement variation. Better measurement accuracy could be achieved by introducing an EDG with a smaller 3-dB bandwidth ($<$0.4 nm). Second, the spectrum of the conventional FBG is susceptible to drifting 10 pm for 1 °C temperature change [10], which will affect the measured light intensity as well as the frequency. Finally, the Gaussian profile assumption for the sidebands and the EDG transmission channels might induce error in the measurement, but referring to the analysis in [11], this error can be neglected.

The EDG interrogator used in this work has 15 channels. If the wavelengths of the optical carriers are properly selected, 15 microwave signals can be monitored simultaneously. In addition, since the EDG-based interrogator is in a miniaturized form and no other microwave components except an MZM were used in the system, the proposed approach could potentially lead to a system of compact size, reduced complexity, and low cost.

IV. Conclusion

The feasibility of microwave frequency measurement based on a monolithically integrated EDG interrogator was demonstrated. Initial results from a proof-of-concept experiment showed that the measured frequencies are in very good agreement with the actual frequencies.

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