Instantaneous Microwave Frequency Measurement With Improved Measurement Range and Resolution Based on Simultaneous Phase Modulation and Intensity Modulation

Xihua Zou, Shilong Pan, and Jianping Yao, *Senior Member, IEEE, Member, OSA*

***Abstract*—A novel approach to implementing instantaneous microwave frequency measurement based on simultaneous optical phase modulation and intensity modulation with improved measurement range and resolution is proposed and experimentally demonstrated. The simultaneous optical phase modulation and intensity modulation are implemented using a polarization modulator (PolM) in conjunction with an optical polarizer. The phase- and intensity-modulated optical signals are then sent to a dispersive element, to introduce chromatic dispersions, which results in two complementary dispersion-induced power penalty functions. The ratio between the two power penalty functions has a unique relationship with the microwave frequency. Therefore, by measuring the microwave powers and calculating the power ratio, the microwave frequency can be estimated. Thanks to the complementary nature of the power penalty functions, a power ratio having a faster change rate versus the input frequency, i.e., a greater first-order derivative, is resulted, which ensures an improved measurement range and resolution. The proposed approach for microwave frequency measurement of a continuous-wave and a pulsed microwave signal is experimentally investigated. A frequency measurement range as large as 17 GHz with a measurement resolution of ± 0.2 GHz for a continuous-wave microwave signal and ± 0.5 GHz for a pulsed microwave signal is achieved.**

***Index Terms*—Instantaneous microwave frequency measurement, microwave photonics, optical microwave signal processing, polarization modulation, radar system.**

I. Introduction

MICROWAVE frequency measurement implemented in the optical domain has been considered a promising solution for defense systems where a large frequency measurement range and instantaneous frequency measurement are required. Microwave frequency measurement in the optical domain also offers other advantages such as low loss, light weight, and immunity to electromagnetic interference. In the past few years, numerous optical techniques have been proposed to implement microwave frequency measurement. In [1], a tunable Fabry-Perot interferometer was used as an optical scanning receiver for microwave frequency measurement; a resolution of 90 MHz within a scanning range of 40 GHz was achieved. Due to the long scanning time, the measurement is not instantaneous. For many applications, however, instantaneous frequency measurement is needed. In general, instantaneous frequency measurement in the optical domain can be classified into two categories. In the first category, an optical channelizer is used [2]–[6]. In [2], the spectrum of a microwave signal was measured by modulating the microwave signal on an optical carrier and then sent to a waveguide-based optical phased array, serving as an optical channelizer. A diffraction pattern at the far field was then generated. By using a CCD camera to record the diffraction pattern, the spectrum of the input microwave signal was obtained. The frequency of a microwave signal can also be measured using a high-resolution free-space optical diffraction grating [3]. It was demonstrated that an optical channelizer based on a free-space optical diffraction grating could offer an instantaneous bandwidth greater than 100 GHz with a channel spacing of 1 GHz [3]. A parallel bank of progressively incremented transmission filters formed using phase-shifted chirped gratings can also be used as an optical channelizer for microwave frequency measurement [4]. It was reported in [4], such an optical channelizer could have an instantaneous bandwidth covering 2–18 GHz with a resolution of 2 GHz. A microwave frequency can also be measured by employing an integrated optical Bragg grating Fabry-Perot (BGFP) device [5]. In the system, the microwave signal was modulated on a continuous-wave light wave, which was then spatially separated by the integrated optical BGFP that could provide a resolution of 2 GHz. An optical channelizer can also be realized using a dense wavelength division multiplexer [6], in which an equally spaced multiple wavelengths are combined and then modulated by a microwave signal at an intensity or phase modulator. A high-finesse optical etalon with a free spectral range (FSR) that has a frequency difference with respect to the wavelength spacing of the multi-wavelength source is connected after the modulator, which filters the modulated optical signal with the frequency components of the input microwave signal estimated based on the output powers of the channels of the etalon. In

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the second category, the frequency of a microwave signal can be measured instantaneously over a large bandwidth [7]–[15]. A microwave frequency can be measured by monitoring and comparing two frequency-dependent optical powers [7]–[9] or two frequency-dependent microwave powers [10]–[15]. The frequency measurement resolution can be as high as 0.1 or 0.2 GHz. In [7], the microwave signal with the frequency to be measured is intensity-modulated on two optical carriers. An optical comb filter was employed, with the intensity-modulated optical carriers placed at the peak and the valley of the comb filter spectral response, to generate two complementary optical power functions such that the microwave frequency could be estimated from the power ratio between the two detected optical powers. The technique in [7] was improved by replacing the comb filter with an optical complementary filter pair [8], [9], which simplifies the system since only a single laser source is required. The measurement errors due to the power fluctuations of the two laser sources existing in the two-wavelength system [7] were completely eliminated. The frequency of a microwave signal can also be measured by comparing the microwave powers of the signal that travels in two channels that experience different dispersion-induced power penalties [10], [11]. Again, the microwave signal is intensity-modulated on two optical carriers at different wavelengths. When the intensity-modulated signals pass through a dispersive element, such as a multichannel chirped fiber Bragg grating (MCFBG) [10] or a dispersive fiber [11], the two intensity-modulated signals would experience different chromatic dispersions, leading to different power penalties. The microwave frequency is then estimated from the power ratio between the two detected microwave powers. The measurement range and resolution can be adjusted by simply adjusting the wavelength spacing of the two laser sources or the dispersion of the dispersive element [11]. Some other techniques have also been recently proposed for microwave frequency measurement, which include 1) the use of a dual-output Mach-Zehnder modulator (MZM) operating at the chirp modulation mode with a wide and tunable measurement range [12]; 2) the use of a microwave mixer fed by an input microwave signal and a fixed local oscillator signal to generate a mixing component. By applying the input microwave signal and the mixing component to two intensity modulators, two double-sideband-modulated signals with complementary microwave power response functions would be generated. The microwave frequency is then measured by comparing the two power response functions [13]; and 3) the use of two modulators in series to realize a simple photonic microwave filter with a frequency response that establishes a relationship between the microwave frequency and output microwave power [14], [15]. Note that, an oscillatory behavior was observed in the established relationship between the input frequency and the detected dc voltage in [14], [15], therefore the frequency measurement was only achieved within a relatively small measurement range. To avoid measurement ambiguity, an electronic low-pass or bandpass filter is needed to pre-filter the input microwave signal to ensure the input signal having a frequency falling in the frequency band of interest.

The approaches discussed above are suitable for frequency measurement of a microwave signal with a single frequency. Very recently, a new technique that is suitable for frequency measurement of a microwave signal having multiple frequencies using a chirped fiber Bragg grating was proposed [16]. Thanks to the dispersion of the chirped fiber Bragg grating, the frequency information of the microwave signal is mapped to the time delay difference between the upper and lower sidebands of a double-sideband-modulated signal, leading to the estimation of the multiple frequencies. Due to the ability in multiple-frequency measurement, the technique in [16] is particularly useful for applications in a spectrally cluttered environment.

The approaches based on microwave power monitoring in [10], [11] are advantageous due to their simple architectures, such as the use of a single modulator. On the other hand, the approaches in [10], [11] has a major limitation: the measurement range is limited. The key reason of a small measurement range is due to the fact that the two microwave power penalty functions have an identical variation trend, especially at the lower frequency end. Therefore, a high measurement resolution is obtained only in a narrow frequency band at higher microwave frequencies. To extend the measurement range, the measurement resolution has to be compromised.

In this paper, we propose and experimentally demonstrate a novel approach to implementing instantaneous microwave frequency measurement based on simultaneous optical phase modulation and intensity modulation with improved measurement range and resolution. The simultaneous optical phase modulation and intensity modulation are realized using a single polarization modulator (PolM) in conjunction with an optical polarizer. In the system, the microwave signal with its frequency to be measured is applied to the PolM via the RF port to modulate two linearly polarized optical light waves at different wavelengths from two laser sources. The PolM is a special phase modulator that supports both transverse electric (TE) and transverse magnetic (TM) modes, but with opposite phase modulation indices [17]. The polarization direction of one light wave is aligned with one principal axis of the PolM. The light wave is then phase modulated. The polarization direction of the other light wave is oriented at an angle of 45° with respect to the principal axis of the PolM. Since the optical polarizer is connected with its transmission axis oriented at an angle of 45° to the same principal axis of the PolM, the phase modulated signals along the two principal axes are projected to the transmission axis of the optical polarizer, leading to the generation of an intensity-modulated signal. Both the intensity-modulated and the phase-modulated optical signals are then sent to a dispersive element. Due to the chromatic dispersion of the dispersive element, two dispersion-induced power penalty functions that are complementary are obtained. The phase-modulated and the intensity-modulated signals are then separated by two optical filters and converted to electrical signals at two photodetectors, with the microwave powers measured by microwave power meters. Since there is a unique relationship between the microwave frequency and the power ratio, the microwave frequency is estimated by measuring the two microwave powers. Thanks to the complementary nature of the dispersion-induced power penalty functions, the ratio between the two power penalty functions has a large slope over a large frequency range. Therefore, an improved measurement range and resolution can be achieved.

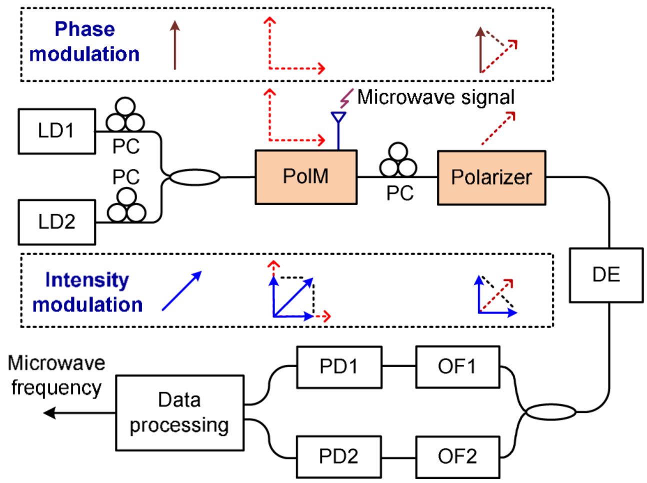

Fig. 1. Schematic diagram of the proposed microwave frequency measurement system. PC: polarization controller; PolM: polarization modulator; DE: dispersive element; PD: photodetector, OF: optical filter, LD: laser diode.

The proposed approach is experimentally investigated for the frequency measurement of a continuous-wave and a pulsed microwave signals. A measurement range of 17 GHz with a measurement resolution of ± 0.2 GHz for a continuous-wave microwave signal and ± 0.5 GHz for a pulsed microwave signal is achieved.

II. Principle

The schematic of the proposed system for instantaneous microwave frequency measurement is shown in Fig. 1. The microwave signal with its frequency to be measured is applied to the PolM via its RF port to modulate two linearly polarized CW light waves from two laser diodes (LDs), with one (LD1) having its polarization direction alighted with one principal axis of the PolM and the other (LD2) having its polarization direction oriented at an angle of 45° to the same principal axis by using two polarization controllers (PCs). The PolM is a special phase modulator that supports both TE and TM modes but with opposite phase modulation indices [17]. A polarizer is connected at the output of the PolM with its transmission axis oriented at an angle of 45° to the same principal axis of the PolM. Since the polarization direction of the light wave from LD1 is aligned with the principal axis of the PolM, a phase-modulated signal along the principal axis is generated, which is projected to the transmission axis of the polarizer. The polarization direction of the light wave from LD2 has an angle of 45° with respect to the principal axis, therefore, at the output of the PolM two phase-modulated signals with opposite phase modulation are generated, which are then projected to the transmission axis of the polarizer, leading to the generation of an intensity-modulated signal. The phase-modulated and the intensity-modulated signals are then launched into a dispersive element. Due to the chromatic dispersion of the dispersive element, two power penalty functions that are complementary in nature are obtained. The two light waves are then separated by two optical filters and sent to two photodetectors. The microwave powers are then measured and used to estimate the microwave frequency.

Under a small signal modulation condition, the electric fields of the phase-modulated and the intensity-modulated signals, $E_{\mathrm{PM}}(t), E_{\mathrm{IM}}(t)$, at the output of the polarizer can be written as

$$\begin{aligned}
E_{\mathrm{PM}}(t) &= \frac{\sqrt{2}}{2}\sqrt{I_1}\cos[\omega_1 t - \beta\cos(\Omega t)] \\
&\approx \frac{\sqrt{2}}{2}\sqrt{I_1}\{J_0(\beta)\cos(\omega_1 t) \\
&\quad + J_1(\beta)\cos[(\omega_1+\Omega)t + 3\pi/2] \\
&\quad + J_{-1}(\beta)\cos[(\omega_1-\Omega)t - 3\pi/2]\}
\end{aligned} \tag{1a}$$

$$\begin{aligned}
E_{\mathrm{IM}}(t) &= \frac{1}{2}\sqrt{I_2}\{\cos[\omega_2 t + \beta\cos(\Omega t) + \pi/2] \\
&\quad + \cos[\omega_2 t - \beta\cos(\Omega t)]\} \\
&\approx \frac{1}{2}\sqrt{I_2}\{J_0(\beta)[\cos(\omega_2 t) + \cos(\omega_2 t + \pi/2)] \\
&\quad + J_1(\beta)(\cos[(\omega_2+\Omega)t + \pi] + \cos[(\omega_2+\Omega)t + 3\pi/2]) \\
&\quad + J_{-1}(\beta)(\cos[(\omega_2-\Omega)t] + \cos[(\omega_2-\Omega)t - 3\pi/2])\}
\end{aligned} \tag{1b}$$

where $I_1, I_2, \omega_1, \omega_2$ are the intensities and angular frequencies of the light waves from the two LDs, $J_k(\cdot)$ is the k-th order Bessel function of the first kind, β is the phase modulation index, and Ω is the angular frequency of the microwave signal.

After passing through a dispersive element, the phase-modulated and intensity-modulated signals would experience chromatic dispersions, which lead to two power penalty functions. At the outputs of the photodetectors, the detected microwave powers for the phase-modulated [18] and intensity-modulated signals [19] are given by

$$P_{\mathrm{PM}}(f) = \frac{1}{2}\Re I_1[J_0(\beta)J_1(\beta)]^2[\sin(\pi\chi_1\lambda_1^2 f^2/c)]^2 \tag{2a}$$

$$P_{\mathrm{IM}}(f) = \Re I_2[J_0(\beta)J_1(\beta)]^2[\cos(\pi\chi_2\lambda_2^2 f^2/c)]^2 \tag{2b}$$

where $\Re$ is the responsivity of the photodetectors (assuming the two photodetectors have an identical responsivity), c is the light velocity in vacuum, λ_1 and λ_2 are the wavelengths of the two light waves, χ_1, χ_2 are the total chromatic dispersions of the dispersive element at λ_1 and λ_2, and f is the frequency of the microwave signal.

If $I_1 = 2I_2$, which can be achieved by controlling the optical powers of the two LDs, we establish a unique relationship between the microwave frequency and the power ratio, given in (3). It is clearly seen from (3) the microwave frequency is uniquely determined by the microwave power ratio. Since the microwave power ratio is independent of the microwave powers, the proposed approach is suitable for microwave frequency measurement under different microwave power levels

$$\gamma(f) = \frac{P_{\mathrm{PM}}(f)}{P_{\mathrm{IM}}(f)} = \frac{\left[\sin\left(\frac{\pi\chi_1\lambda_1^2 f^2}{c}\right)\right]^2}{\left[\cos\left(\frac{\pi\chi_2\lambda_2^2 f^2}{c}\right)\right]^2} \tag{3}$$

In addition, thanks to the complementary nature of the two power penalty functions, a power ratio function that has a faster change rate versus the input frequency, i.e., a larger first-order derivative is ensured in a wide frequency range, which is the

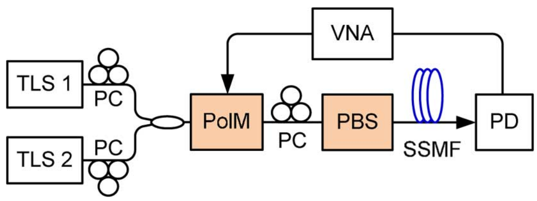

Fig. 2. Experimental setup. TLS: tunable laser source; PC: polarization controller; PolM: polarization modulator; PBS: polarization beam splitter; VNA: vector network analyzer; SSMF: standard single-mode fiber; PD: photodetector.

key significance of the proposed technique. It is different from the approaches in [10], [11], where a large dispersion difference is usually required to ensure a large measurement range. In the proposed approach, a small or even a zero-dispersion difference would ensure a power ratio function having a high first-order derivative at a wide measurement range. Therefore, the microwave frequency can be measured using a dispersive element with a small dispersion or the two light waves can have a small wavelength spacing.

III. Frequency Measurement for a Continuous-Wave Microwave Signal

Since (3) is derived for a continuous-wave microwave input signal, an experiment is firstly performed to measure the frequency of a continuous-wave microwave signal. The experimental set up, shown in Fig. 2, consists of two tunable laser sources, a PolM (Versawave Technologies [17]), a polarization beam splitter serving as a polarizer, a 10-km single-mode fiber serving as a dispersive element, and a photodetector. The two light waves from the two tunable laser sources emitting at 1549.5 and 1550 nm are simultaneously phase- and intensity-modulated by a microwave signal that is generated by a vector network analyzer (VNA, Agilent E8364A). In the experiment, to avoid using two optical filters to separate the two optical signals, the power penalty functions are measured for the phase- and intensity-modulated signals separately by switching on only one tunable laser source at one time.

The output power of the continuous-wave microwave from the VNA is set as 0 dBm. The microwave power penalty functions measured by the VNA at the two wavelengths are shown in Fig. 3. It is clearly seen that the power penalty function are complementary. The simulated power penalty functions are also shown in Fig. 3, an excellent agreement is observed. Based on the two measured microwave power penalty functions, the power ratio function is calculated which is shown in Fig. 4. As can be seen a monotone power ratio function extending over a large frequency range from 2 to 19 GHz with a large slope over the entire frequency range is obtained. A theoretical power ratio function calculated based on (3) is also shown in Fig. 4. An excellent agreement is also observed.

By measuring the microwave powers and calculating the power ratio, the microwave frequency is then estimated. Fig. 5 shows the measured microwave frequency when the input frequency is tuned from 2 to 19 GHz. Since the power ratio function has a large first-order derivative, a measurement range as large as 17 GHz (2–19 GHz) is obtained for a measurement resolution of ± 0.2 GHz. As discussed earlier, the key reason that the measurement range and the resolution are improved is that the power ratio function has a higher first-order derivative resulted due to the complementary nature of the two power penalty functions.

In addition, to confirm that the frequency measurement is independent of the microwave power, as indicated by (3), the output power from the VNA is tuned at four power levels of 0, -5, -10, and -15 dBm. For the purpose of comparison, the measurement errors under the four microwave power levels are also given in Fig. 6, which shows an identical measurement

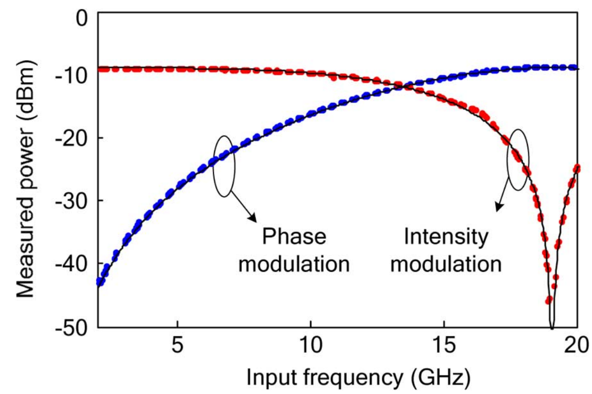

Fig. 3. Measured and simulated microwave power functions for the phase- and the intensity-modulated signals. The microwave power at the output of the VNA is set as 0 dBm. (Dotted line: measured data; Solid line: theoretical data).

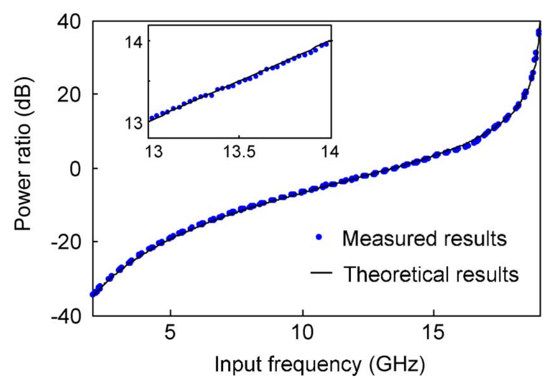

Fig. 4. Comparison between the theoretical and experimental power ratio functions. A monotone power ratio function extending over a large frequency range with a large slope over the entire frequency range is observed. The inset gives a zoom-in view of the power ratio functions.

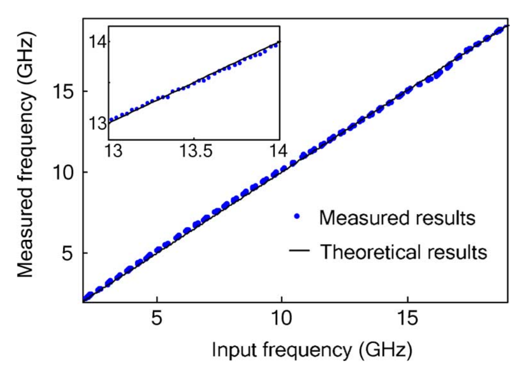

Fig. 5. Measured microwave frequencies when the input microwave frequency is tuned from 2 to 19 GHz. The inset gives a zoom-in view of the measured microwave frequencies.

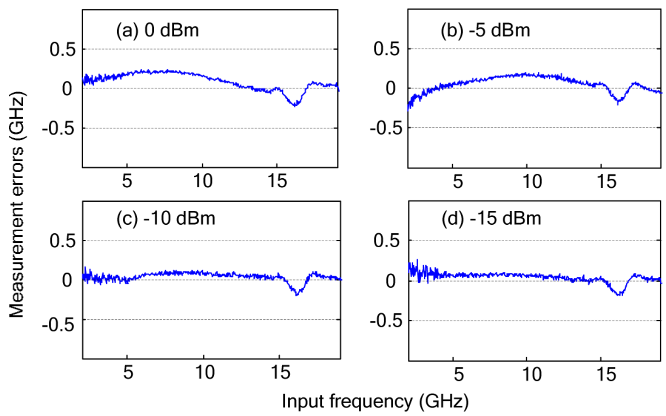

Fig. 6. Comparison of the measurement errors at four microwave power levels: (a) 0 dBm, (b) -5 dBm, (c) -10 dBm, (d) -15 dBm.

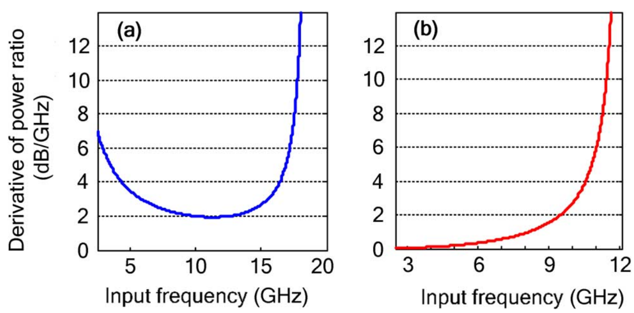

Fig. 7. The first-order derivatives of the power ratio functions: (a) the proposed approach with simultaneous phase and intensity modulations, (b) the approach with intensity modulation only proposed in [11].

range of 2–19 GHz and an identical maximum measurement error of ± 0.2 GHz.

Since the improvement in measurement range and resolution is directly associated with the slope of the power ratio function, to have a better understanding of the performance improvement, an additional simulation is made to compare the first-order derivatives of the power ratio functions for a frequency measurement system with only intensity modulation and with simultaneous phase and intensity modulations.

In the simulation, the parameters for the system are chosen identical to those used in the experiment: the wavelengths of the two laser sources are 1549.5 and 1550 nm and the dispersive element is a 10-km single mode fiber. For the system proposed in [11], the wavelengths of the two laser sources are 1470 and 1600 nm and the dispersive element is a 20-km single-mode fiber. Then the slopes of the two power ratio functions are obtained by calculating the first-order derivatives of the power ratio functions, as shown in Fig. 7(a) and (b).

As can be seen the first-order derivative of the power ratio function for the proposed approach is greater than 2 dB/GHz in the 2–19 GHz range. On the other hand, a much smaller range of 9.5–11.5 GHz is obtained when the first-order derivative is greater than 2 dB/GHz for the approach using intensity modulation only. The results confirm that the proposed approach can provide a significantly improved measurement range for a given measurement resolution. It should be noted that the measurement range with a high resolution in Fig. 6(a) is greater than that in Fig. 6(b), even though a much smaller wavelength spacing (or a smaller chromatic dispersion) is used. Thus, if identical parameters are adopted to calculate the first-order derivatives for the two approaches, a much smaller measurement range would be resulted for the approach in [11], which confirms a further improvement in the measurement range and resolution for the proposed approach.

For a continuous-wave microwave signal, the power level at the receiver is usually low. To ensure an acceptable frequency measurement accuracy, a minimum required power level must be met to ensure a good signal-to-noise ratio (SNR). In the analysis, we assume that the power level at a microwave receiver is not lower than -100 dBm which is a medium power level for practical systems, such as a military system, a mobile system, and a satellite communications system, or not lower than -70 dBm for commercially available wideband power meters [20].

Based on our numerical simulations, a minimum SNR of 18.5 dB is required to ensure that the measurement errors are less than ± 0.2 GHz, and the maximum power fading induced by chromatic dispersion here is 25 dB for the frequency range of 3–18 GHz. Therefore, under a first power benchmark of -100 dBm, at the output of the photodetector the microwave power should be greater than -56.5 dBm. Since the dispersion-induced power fading is subtracted from the total microwave power, the microwave current from the photodetector is determined by the power of the laser source, the phase modulation index and the photo responsivity of the photodetector, which is expressed as $i_m^2 = [\Re \times I_0 J_0(\beta) J_1(\beta)]^2$, where I_0 is the output power of the laser source. Then the corresponding microwave power $P_m = (i_m^2 \times 50)/2$ should be greater than -56.5 dBm if a 50-Ω terminal is connected to the photodetector. It should be pointed out that the power expression is obtained considering that all optical losses in the system are compensated by an erbium-doped fiber amplifier (EDFA). If the output power of the laser source is 10 dBm and the responsivity of the photodetector is 0.4 A/W, the phase modulation index $\beta = \pi \times a/V_\pi$ should be greater than 4.8×10^{-3} to ensure that the detected microwave power is greater than -56.5 dBm, where a is the amplitude of the microwave signal and V_π is the half-wave voltage of the PolM. Consequently, a minimum received microwave power of -35 dBm (or $a > 5.3$ mv), which is derived considering the half-wave voltage of the PolM is 3.5 v at 40 Gb/s, is sufficient to provide a modulation index greater than 4.8×10^{-3}. Namely, a lowest power level of -35 dBm is required to perform the frequency measurement in the proposed approach.

In addition, a second power benchmark is set as -70 dBm. Based on a similar calculation, at the output of the photodetector the microwave power should be greater than -26.5 dBm, and at the RF port of the PolM a minimum received microwave power should be greater than -5.5 dBm with a phase modulation index greater than 0.15.

IV. Frequency Measurement for a Pulsed Microwave Signal

For many warfare applications, such as a radar, the radiated microwave signals in most of the cases are pulse-modulated.

In this section, we will show that the proposed technique can also be used for frequency measurement of a pulsed microwave signal.

Assume a pulsed microwave signal $s_m(t)$ has a fixed carrier frequency f_m, a pulse duration T_1 and a period T. Under the assumption that the input microwave signal is noise-free, the average microwave power $P_{\rm ave}$ is given by

$$P_{\rm ave} = \frac{1}{T}\int_0^{T_1} s_m^2(t)dt = \frac{T_1}{T}P_{\rm cw} \quad (4)$$

where $s_m^2(t)$ is the instantaneous microwave power, $P_{\rm cw}$ is the power of a continuous-wave microwave signal, and T_1/T is the duty cycle. Therefore, the power ratio function would be identical to that for a continuous-wave microwave signal.

For a practical microwave receiver, the input microwave signal is always imbedded in a noise $n_m(t)$. Assume the noise is additive with a zero mean, the average power is given by

$$\begin{aligned} P_{\rm ave} &= \frac{1}{T}\int_0^{T} [s_m(t)+n_m(t)]^2 dt \\ &= \frac{T_1}{T}P_{\rm cw} + P_n \end{aligned} \quad (5)$$

where P_n is the noise power. The power ratio function can now be re-written as

$$\gamma = \frac{\frac{T_1}{T}\times[\sin(\pi\chi_1\lambda_1^2 f^2/c)]^2 + P_n}{\frac{T_1}{T}\times[\cos(\pi\chi_1\lambda_1^2 f^2/c)]^2 + P_n}. \quad (6)$$

From (6) we can see, for a given measurement accuracy, the required SNR should be increased, or for a given measurement range, the measurement resolution would be reduced, compared with a continuous-wave microwave signal under an identical noise condition.

A second experiment is then performed to measure the frequency of a pulsed microwave signal. In the second experiment, the pulsed microwave signal is generated by mixing a continuous-wave microwave signal from the VNA and a 500-Hz square-wave with a duty cycle of 33%. When the microwave frequency is tuned from 2 to 19 GHz, the measured microwave power penalty functions for the phase modulation and the intensity modulation are recorded, which are shown in Fig. 8. As can be seen, two dispersion-induced power penalty functions that are complementary are obtained. Compared with the power penalty functions in Fig. 3, larger power ripples are observed, which are resulted from the lower SNR due to the input signal is pulsed. As a result, within the same measurement range of 2–19 GHz, the maximum measurement error is increased from ±0.2 GHz to ±0.5 GHz, as shown in Fig. 9.

Like most of the frequency-amplitude mapping techniques, the proposed approach can only be used for the frequency measurement of a continuous-wave or pulsed microwave signal with a fixed carrier frequency. For applications where the microwave signal has multiple frequencies or the signal is imbedded in a spectrally cluttered environment, this proposed approach is not applicable.

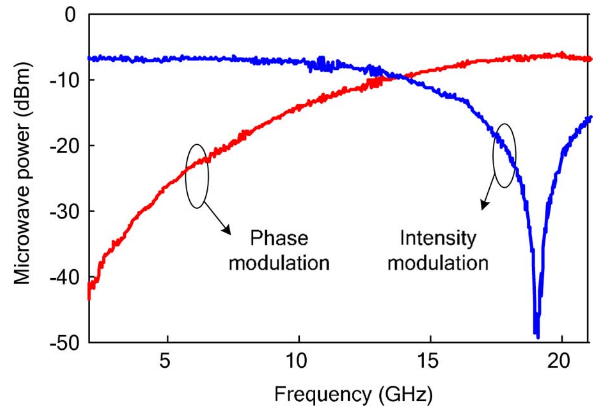

Fig. 8. Measured microwave power functions when a pulse-modulated microwave signal is applied to the PolM.

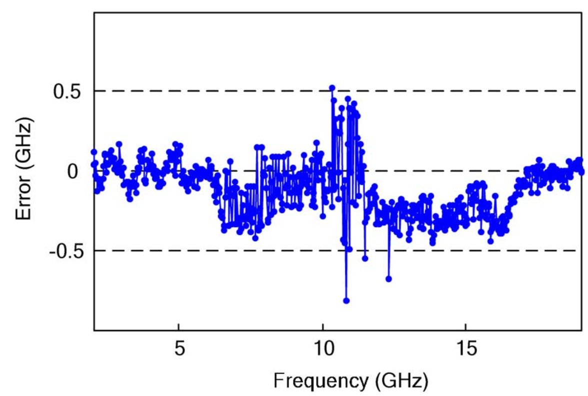

Fig. 9. Distribution of measurement errors for pulse-modulated microwave signal when the input microwave frequency is tuned from 2 to 19 GHz.

V. Conclusion

We have proposed and experimentally demonstrated a novel approach to implementing instantaneous microwave frequency measurement with improved frequency measurement range and resolution. The fundamental principle of the approach lies in the implementation of simultaneous phase modulation and intensity modulation. Thanks to the complementary nature of the power penalty functions of the phase-modulated and intensity-modulated signals passing through a dispersive element, a power ratio function having a greater first-order derivative over a large frequency range was achieved, leading to an improved frequency measurement range and resolution. In the proposed approach, the simultaneous phase modulation and intensity modulation were realized using a PolM in conjunction with an optical polarizer. Two experiments were performed. In the first experiment, the microwave frequency of a continuous-wave microwave signal was measured. A frequency measurement range as large as 17 GHz with a measurement resolution of ±0.2 GHz was demonstrated. The independence of the frequency measurement on the input microwave power level was also confirmed, where similar measurement errors were obtained under four different microwave power levels. In the second experiment, the frequency of a pulsed microwave signal was measured. For an identical measurement range of 2–19 GHz, a poorer measurement resolution of ±0.5 GHz was resulted.

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