Instantaneous Microwave Frequency Measurement Using an Optical Phase Modulator

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***Abstract*—A novel technique for instantaneous microwave frequency measurement using an optical phase modulator is proposed and demonstrated. In the proposed system, a microwave signal with its frequency to be measured is modulated on two optical wavelengths at the phase modulator, with the phase-modulated optical signals sent to a dispersive element, and detected at two photo-detectors. Due to the chromatic dispersion of the dispersive element, the two microwave signals will experience different power fading, leading to different power versus frequency functions. A fixed relationship between the microwave frequency and the microwave powers is established. By measuring the microwave powers, the microwave frequency is estimated. Compared with the techniques using an intensity modulator, the proposed approach is simpler with less loss. Since no bias is needed the system has a better stability, which is highly expected for defense applications. Experimental verification is presented.**

***Index Terms*—Microwave frequency measurement, microwave photonics, phase modulation.**

I. Introduction

MICROWAVE receiver for radar and other electronic warfare applications require the capability to estimate the frequency of an unknown microwave signal over a wide bandwidth. Conventional techniques for instantaneous microwave frequency measurement are thought to be bulky, limited in bandwidth, and suffer from electromagnetic interference. Due to the advantages such as high bandwidth, light weight, low loss, and immunity to electromagnetic interference, photonic technology for microwave signal processing has been considered a promising solution recently [1]–[3]. A number of approaches have been proposed for the measurement of a microwave frequency in the optical domain [4]–[9]. A microwave frequency can be measured using an intensity modulator in conjunction with a dispersive element. In a microwave photonic transmission system employing double-sideband (DSB) modulation, the received microwave power is dependent on the microwave frequency due to the chromatic dispersion in the optical link. The frequency-dependent power variation of the received RF signal in an intensity-modulation-based system has been employed to measure the frequency of a microwave signal [4]. An improved method with adjustable measurement range and resolution was recently presented in [5]. Novel approaches based on dc optical power monitoring using low-speed optical power meters with reduced system cost were demonstrated in [6], [7]. Microwave frequency measurement using two cascaded Mach-Zehnder modulators (MZMs), a RF delay line and a single photodetector were also demonstrated to estimate the frequency of a microwave signal [8], [9].

The major difficulty associated with the use of an MZM for microwave frequency measurement is the need for a sophisticated electrical circuit to control the dc bias, to stabilize the operation of the MZM. In this letter, a novel technique to measure the frequency of a microwave signal using an optical phase modulator is proposed. The key significance of the proposed approach is that the phase modulator is not biased, which eliminates the bias drifting problem, a feature that is highly expected in defense systems [10], [11]. In addition, a phase modulator is simpler and has smaller insertion loss. The proposed technique is experimentally demonstrated. An excellent agreement between the theoretical predictions and experimental results is achieved.

II. Principle of Operation

The system configuration of the proposed technique is shown in Fig. 1. The system consists of two laser diodes (LDs), a wavelength multiplexer, an optical phase modulator, a length of dispersive fiber serving as the dispersive element, a wavelength demultiplexer, and two photo-detectors (PDs). The light waves at different wavelengths from the two LDs are combined by the multiplexer and sent to the phase modulator. An unknown RF signal is applied to the phase modulator to phase-modulate the two optical carriers. The modulated optical signals propagate in the dispersive fiber, which are then separated by the demultiplexer and converted to electrical signals at the two PDs. Since the dispersion coefficients are different for the two carriers, the detected RF powers are different for the two channels. The difference in the detected RF powers will be used to determine the frequency of the unknown RF signal.

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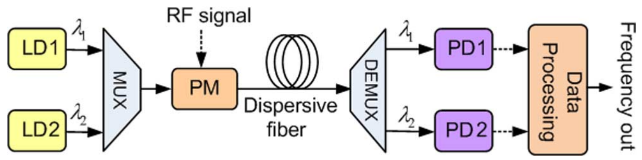

Fig. 1. Schematic of the proposed approach for instantaneous microwave frequency measurement. (LD: laser diode; PM: phase modulator; PD: photodetector; MUX/DEMUX: multiplexer/demultiplexer).

The electrical power of a phase modulated microwave signal traveling in a dispersive link is a function of the microwave frequency, which is given by [3]

$$P \propto \sin^2\left(\frac{\pi\chi\lambda^2 f^2}{c}\right) \quad (1)$$

where c is the light velocity in a vacuum, χ is the accumulated dispersion of the fiber link in ps/nm, λ is the wavelength of the optical carrier, f is the frequency of the modulating microwave signal to be measured.

In order to determine the microwave frequency, two different wavelengths are needed. Assume that the powers from the two LDs and the losses of the two wavelength channels are identical, then we have the power ratio between the two wavelength channels

$$\gamma = \frac{\sin^2\left(\frac{\pi\chi_1\lambda_1^2 f^2}{c}\right)}{\sin^2\left(\frac{\pi\chi_2\lambda_2^2 f^2}{c}\right)} \quad (2)$$

where λ_1 and λ_2 are the wavelengths of the two optical carriers, χ_1 and χ_2 are the corresponding accumulated dispersions of the two channels.

As can be seen the power ratio is independent of the input RF powers. For a system with given wavelengths and accumulated dispersions, the microwave frequency can be calculated if the power ratio is known. Therefore, by simply measuring the microwave powers at the outputs of the two channels, the microwave frequency can be estimated.

First, we investigate the proposed technique by simulations. The simulations are performed based on a system with the two optical wavelengths at 1520 and 1630 nm, and the accumulated dispersions of 362 and 512 ps/nm, which correspond to the dispersions of 25 km standard single mode fiber. Fig. 2(a) shows the calculated RF power distribution versus the microwave frequency obtained based on (1). Fig. 2(b) shows the distribution of the power ratio versus the microwave frequency, calculated based on (2). To estimate the microwave frequency based on the power ratio without ambiguity, a monotone interval should be chosen. Different monotone intervals of the power ratio function correspond to different spectral ranges. For most of the applications, the first monotone interval is usually selected, with the upper and the lower limits determined by two factors. The upper limit is determined by the first notch of the power ratio curve, which is given by

$$f_{up} = \sqrt{\frac{c}{\chi_{\max}\lambda_{\max}^2}} \quad (3)$$

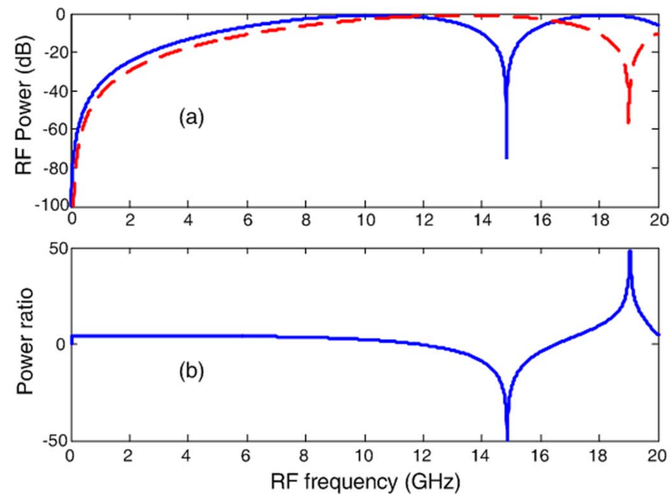

Fig. 2. Simulation results. (a) RF power versus microwave frequency (solid: $\lambda_1 = 1520$ nm, $\chi_1 = 362$ ps/nm; dashed: $\lambda_2 = 1630$ nm, $\chi_2 = 512$ ps/nm); (b) Power ratio versus microwave frequency.

where $\chi_{\max}$ is the larger dispersion, and $\lambda_{\max}$ is the corresponding wavelength.

It is seen that the power ratio distribution at the lower frequency range is flat due to a small difference between the detected RF powers. The flat power ratio distribution would lead to a large measurement error since a small measurement error in the microwave powers would cause a large power ratio error. The lower limit f_{lo} is thus determined by the predetermined measurement error tolerance. The total measurement range of the system with a given measurement accuracy is

$$BW = f_{up} - f_{lo}. \quad (4)$$

On the other hand, if the second monotone interval is chosen, the upper and lower limits would be determined by the positions of the first notches of the two power distribution functions. However, a bandpass filter should be used to eliminate the frequencies from outside the frequency range.

III. Experiment

An experiment based on the setup shown in Fig. 1 is implemented. Two wavelengths from two tunable laser sources (Agilent 81940A) with each having an output power of 6 dBm are multiplexed and then sent to the phase modulator. A microwave signal generated by a vector network analyzer (VNA, Agilent 8720ET) is applied to the phase modulator via the RF port to modulate the two optical wavelengths. The microwave frequency is tunable from 50 MHz to 20.05 GHz. The modulated optical carriers are sent to the 25.6 km single mode fiber. At the output of the fiber, the two phase-modulated signals are seperated by the demultiplexer and then sent to the two PDs. The RF powers of the two microwave signals are measured by the VNA. The RF frequency is thus estimated.

In the experiment, two power distribution functions are first measured using the VNA, with the two wavelengths set at 1520 and 1620 nm. The power ratio function is calculated, which is shown in Fig. 3(a). Then, we tune the frequency of the input microwave signal and record the measured frequency. The results

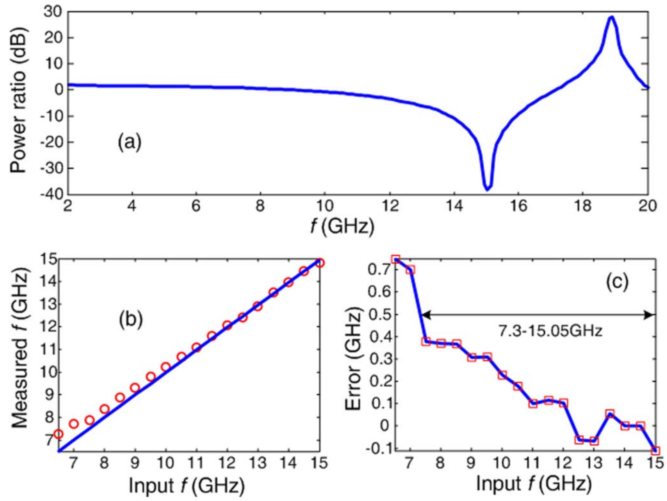

Fig. 3. Experimental results ($\lambda_1 = 1520$ nm, $\lambda_2 = 1620$ nm). (a) Power ratio function; (b) measured frequency versus input frequency; (c) measurement errors for a measurement range of 7.3–15.05 GHz.

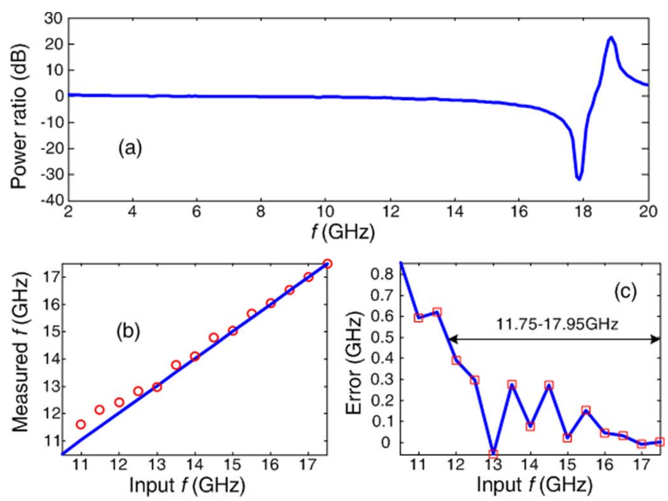

Fig. 4. Experimental results ($\lambda_1 = 1520$ nm, $\lambda_2 = 1540$ nm). (a) Power ratio function; (b) measured frequency versus input frequency; (c) measurement errors for a measurement range of 11.75–17.95 GHz.

are shown in Fig. 3(b) as circles. The measurement errors calculated by comparing the measured frequencies and the input frequency are shown in Fig. 3(c). It can be seen that for a given measurement accuracy, say ± 0.5 GHz, the measurement range is 7.3–15.05 GHz.

If a third wavelength is used, a second power ratio function would be obtained, leading to a different measurement range [5]. For example, if we introduce a third wavelength at 1540 nm, a second power ratio function calculated according to the RF powers at 1520 and 1540 nm are obtained, as shown in Fig. 4(a). Fig. 4(b) shows the frequency measurement results. The measurement errors are calculated, which are shown in Fig. 4(c). In this case, the measurement range is 11.75–17.95 GHz with a measurement accuracy of ± 0.5 GHz. There is a tradeoff between the measurement range and the measurement accuracy. Higher measurement accuracy results in a smaller measurement range, while a lower measurement accuracy would lead to a relatively large measurement range. For example, in the first case of the experiment, the measurement resolution is ± 0.1 GHz corresponding to a measurement range of 11.0–15.0 GHz. The measurement accuracy achieved here is comparable to that of the previous works [4]–[6], which is acceptable for applications where a rough but instantaneous microwave frequency estimation is required. We believe that the noise generated in the PD is the major source of measurement error. The influence of the wavelength stability on the system performance is also studied. It is estimated that a wavelength drift of 0.1 nm would lead to an additional measurement error of about 5 MHz for the first case of the experiment.

IV. Conclusion

We have proposed and experimentally demonstrated a novel technique for instantaneous microwave frequency measurement using an optical phase modulator. The frequency of a microwave signal was estimated by measuring the microwave powers at the outputs of the two PDs, with the two microwave signals carried by two different optical wavelengths that were experiencing different power fading. The key significance of the proposed approach is the use of an optical phase modulator. Since no bias was needed, the biasing drifting problem existing in an MZM-based system was completely eliminated, leading to improved system stability. This feature is highly expected in the defense systems. In addition, the use of an optical phase modulator makes the system simpler with lower loss, which is also desirable for defense applications.

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