Instantaneous Microwave Frequency Measurement Using a Photonic Microwave Filter With an Infinite Impulse Response

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***Abstract*—A photonic technique for instantaneous microwave frequency measurement is proposed. In the proposed technique, a photonic microwave filter having a monotonic frequency response with the magnitude varying from positive infinity to negative infinity on a log scale, is constructed by cascading two photonic microwave filters with one having an infinite impulse response and the other having a finite impulse response. For a single-frequency microwave signal with a normalized magnitude, a unique relationship between the output response and the input frequency is established. Since the response extends from positive to negative infinity, for a given measurement range, a significantly increased measurement resolution is achieved. The proposed technique is verified by an experiment.**

***Index Terms*—Instantaneous frequency measurement (IFM), microwave photonics, photonic microwave filter.**

I. Introduction

FOR many defense applications, instantaneous frequency measurement (IFM) of a microwave signal is required to enable scanning, identification, and analysis of the microwave signal over a large frequency range with a high probability of interception (POI). In some defense systems, such as radar and other electronic warfare (EW) systems, a number of specialized receivers are jointly employed to reduce the processing load of a single receiver. Therefore, the carrier frequency of a microwave signal is needed to be measured instantaneously using an IFM receiver before passing it to a specialized receiver for further processing [1]. However, it is difficult to realize IFM using conventional electronic solutions in which the frequency scan or sweeping is performed with a limited frequency range, but at a higher power consumption and poorer immunity to electromagnetic interference (EMI).

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To overcome these limitations, photonic approaches have been proposed. An optical channelizer has the ability to analyze the spectrum of multiple microwave signals [2], [3]. However, it requires a diffraction grating and a photodetector (PD) array which would limit the measurement range and resolution to 20 and 1 GHz, respectively. Frequency-to-time mapping technique can also be used to measure the frequencies of multiple signals [4], but a high-speed oscilloscope is required.

For frequency measurement of a single-frequency signal, IFM techniques based on optical or microwave power monitoring are attractive because of the large frequency measurement range and high measurement resolution [1], [5]–[13]. The basic concept is to construct an amplitude comparison function (ACF) which is the ratio between two different optical or microwave power functions. In [1], [5], and [6], chromatic dispersion induced power fading functions were used; to achieve a high resolution, the measurement range is limited to a few gigahertz in the vicinity of the lower frequency notch. To get high measurement accuracy while maintaining a wide measurement range, the laser wavelength has to be tuned or multiple wavelengths should be used. Still, it is difficult to perform an accurate measurement at low frequencies because of a small ACF slope. To achieve a wider measurement range without the need for wavelength tuning, two complementary direct current (dc) voltage [7] or power [8]–[13] functions were used to construct the ACF, to achieve an ACF with infinite power variation or a large slope over the entire range of measurement. The major limitation of these approaches is the high system complexity: multiple laser sources, electrooptical modulators, and/or other passive components must be used. In addition, the use of multiple laser sources may have problems such as wavelength spacing drift and relative power fluctuations, which may increase the measurement error [7]–[10]. The use of multiple modulators may also increase measurement errors [7]–[9] since the modulators may not be perfectly matched. In [12] and [13], the Mach–Zehnder modulator (MZM) was biased to suppress the optical carrier, but an incomplete carrier suppression will also contribute to measurement errors. We have recently proposed an approach [14] in which only one laser source and one MZM were employed with reduced measurement error. The major limitation of this approach is that it still requires two PDs for getting the ACF and the noise of the PDs contributes to the measurement errors.

In this letter, we propose an improved photonic approach for microwave frequency measurement using a photonic microwave filter with an infinite impulse response (IIR) filter. It is different from the previous approaches in that only one filter response is

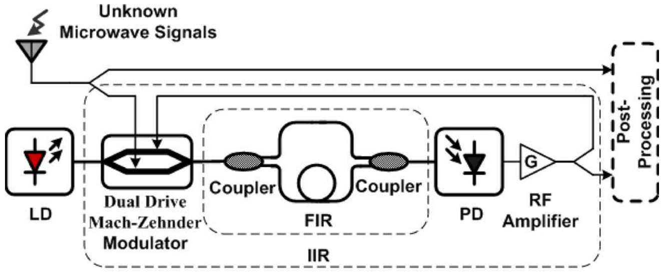


Fig. 1. Schematic diagram of the proposed photonic microwave filter for instantaneous microwave frequency measurement.

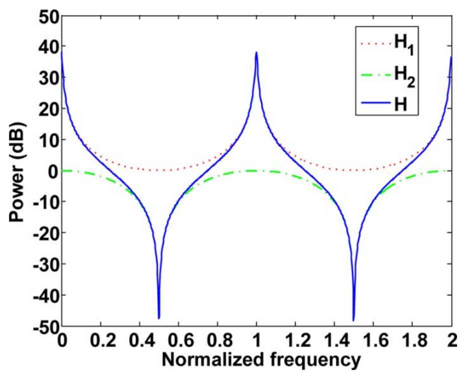


Fig. 2. Calculated frequency response of H_1, H_2, and H for $k = 0.5$, $L = 1$, and $G = 1.95$.

measured, so that only one PD is required. This lowers the expected measurement error; the complexity and cost of the measurement system are also considerably reduced. Moreover, theoretically the power variation of the response is infinite which is similar to the ACF in [14]; therefore, the measurement resolution can be maintained.

II. Operating Principle and Experimental Setup

The system configuration for the proposed photonic microwave frequency measurement is shown in Fig. 1. It consists of an electrical feedback IIR filter cascaded with a finite impulse response (FIR) filter. Linearly polarized continuous-wave (CW) light from a laser diode (LD) is sent to a dual-drive Mach–Zehnder modulator (DD-MZM) which is driven via one radio-frequency (RF) port by a microwave signal for which the frequency is to be measured. The other RF port is connected to the output of the PD to form a recirculating loop. The net gain of the loop is adjusted to avoid oscillations. The transfer function, without considering the FIR filter, is given by

$$H_1(z) = \frac{LRk}{1-(1-k)Gz^{-1}} \tag{1}$$

where L is the total loss including the insertion loss of the RF power divider, the modulator, and the optical fibers, R is the responsivity of the PD, G is the gain of the RF amplifier, and k is the split ratio of the RF power divider. This transfer function has one pole and no zero as shown in Fig. 2.

To have an infinite power variation, a two-tap FIR notch filter, formed by two 3-dB optical couplers, is added to introduce a zero in the transfer function. Its transfer function is

$$H_2(z) = 1 + z^{-1} = \frac{1+z}{z} \tag{2}$$

and the plot is shown in Fig. 2. The total transfer function of the cascaded IIR and FIR filters is

$$H(z) = H_1(z)\cdot H_2(z) = \frac{LRk(1+z)}{z-(1-k)G}. \tag{3}$$

In deriving (3), the time delay difference between the two arms of the FIR filter is set equal to the loop time delay of the IIR filter. The total transfer function H is also plotted in Fig. 2. We can see that, on a log scale, it has infinite power variation, ensuring a high measurement resolution.

With $z = \exp(j2\pi Tf)$, (3) can be rewritten in frequency domain as

$$H(f) = \frac{LRk[1+\exp(j2\pi Tf)]}{\exp(j2\pi Tf)-(1-k)G} \tag{4}$$

where T is the loop time delay and f is the RF frequency. As seen in Fig. 2, the monotonic region of the total transfer function from dc to the first notch can be used as the frequency measurement range. Based on (4), a calibrated look-up table can be established to extract the frequency of the input microwave signal from the output power of the RF coupler.

The output power is actually related to the power of the input microwave signal

$$P_{\text{out}} \propto J_0^2(m)\,J_1^2(m)\,|H(f_m)| \tag{5}$$

where m is the modulation index which is related to the input microwave power, f_m is the unknown microwave frequency, and $J_i(\cdot)$, $i = 0, 1$, are the Bessel functions of the first kind. To ensure that the microwave frequency has a unique relationship with the output power, the input signal power should be normalized. This can be done by tapping a small amount of input power and using the tapped signal to calculate $J_0(m)J_1(m)$ in the postprocessing as shown in Fig. 1.

III. Measured Results and Discussion

A proof-of-concept experiment is carried out for the configuration in Fig. 1. A light wave at 1550 nm generated by a tunable laser source (Anritsu MG9638A) is sent to the dual port MZM (Fujitsu FTM7921ER 10 Gb/s). The IIR filter uses electrical feedback, so it is coherence free. To make the FIR filter also work incoherently, the coherence control of the laser source is turned ON. The resultant laser linewidth is 50 MHz so that the laser coherence length is shorter than the FIR filter arm length difference.

In deriving (3), the time delays of the two filters are assumed identical. Although the time delay of the IIR filter is changed when the FIR filter is incorporated, only the shorter arm of the FIR filter would contribute to the time delay of the IIR filter. Therefore, in the experiment we can match the two time delays by adjusting a tunable optical delay line that is inserted in the longer arm of the FIR filter.

A microwave signal generated by a vector network analyzer [(VNA) Agilent E8364A] is applied to the MZM. The measured transfer function is shown in Fig. 3. The transfer function calculated based on (4) is also shown. A good agreement is observed. Because of the availability of the components, such as the RF amplifier (Avantek SA82-0431) which has a bandwidth from 8 to 18.2 GHz, together with the bandwidths and loss profiles

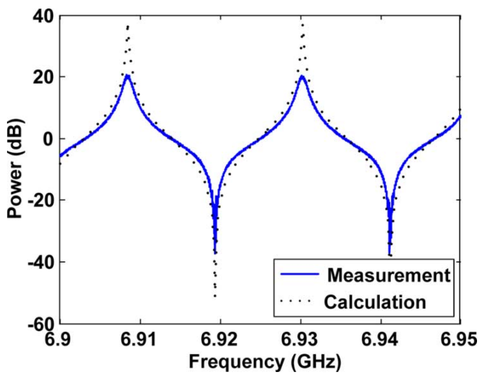
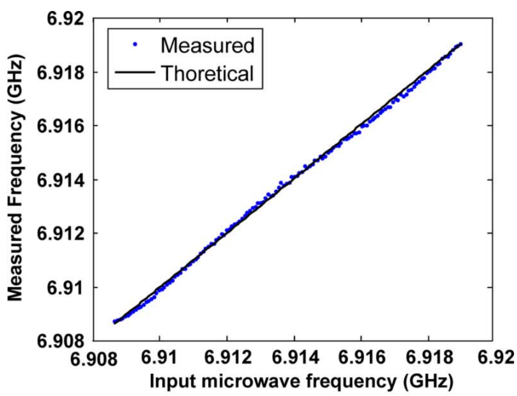
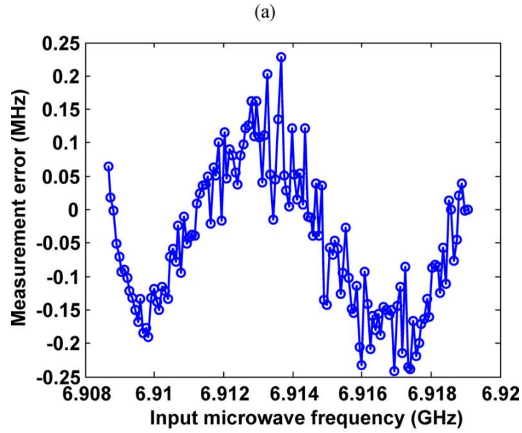


Fig. 3. Measured system transfer function.



(a)



(b)

Fig. 4. (a) Estimated frequency as a function of the input frequency; (b) measurement error versus the input frequency.

of the other components, the maximum RF gain occurs around 6.9 GHz.

The estimated frequency of the microwave signal and the error with respect to the actual input frequency is presented in Fig. 4(a) and (b). The frequency measurement range chosen in our experiment is from 6.9088 to 6.9190 GHz. Note that since the effective loop length of the IIR filter including the optical fiber pigtails and RF cables is very long (9.34 m), a free spectral range (FSR) of 21.8 MHz is observed. For practical applications, the loop length should be reduced, leading to an increased FSR thus an increased measurement range. Considerable reduction in loop length can be achieved using integrated solutions. For instance, a 10-GHz measurement range can be realized with 1-cm effective loop length by using integrated optics with electroabsorption modulator (EAM) as the modulator.

The measurement resolution can be characterized by using the first-order derivative of the power-frequency function. Based on our calculation, the minimum resolution of the proposed configuration is 2.67 dB/GHz for a 10-GHz measurement range, which is much higher than the resolution of 0.19 dB/GHz for a 6.5-GHz range in [5].

IV. Conclusion

We have proposed and experimentally demonstrated a novel approach to photonic microwave frequency measurement using a photonic microwave filter with an IIR. The key significance of the approach is that the transfer function of the filter has infinite power variation, which increases significantly the measurement resolution. In addition, since only a single laser source, a modulator, and a PD were needed, the system complexity was also reduced.

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