Instantaneous Photonic Microwave Frequency Measurement With a Maximized Measurement Range

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Abstract—The use of photonic techniques to achieve frequency-to-power mapping is very attractive for instantaneous microwave frequency measurement. To have a large measurement range and a uniform measurement resolution in the range, to accurately evaluate the center frequency of a continuous-wave (CW) as well as a pulsed microwave signal, and to easily perform calibration of the measurement system, a linear amplitude comparison function (ACF), defined as the ratio of two powers of the microwave signal experiencing different power fading, is highly desirable. In this paper, we propose and demonstrate, for the first time, a novel technique to achieve a linear ACF for microwave frequency measurement with a maximized measurement range. For a measurement resolution of ±0.4 GHz, a measurement range of 0~25 GHz is obtained for a CW microwave signal and a measurement range of 3~18 GHz is achieved for a pulsed microwave signal. The system is potentially integratable in a monolithically chip, which have the desirable features of small size, low cost and stable operations.

I. INTRODUCTION

Identification of the frequency of an intercepted microwave signal from a radar or communication system is of critical importance in the field of electronic warfare (EW). In a defense system, a frequency measurement (IFM) receiver is needed to instantaneously measure the carrier frequency of an unknown microwave signal before passing it to a specialized receiver for further signal processing. Conventional electronic solutions to microwave frequency measurement can achieve high resolution, but it is difficult to realize broadband and instantaneous measurement. Electronic approaches also have the disadvantages such as high power consumption, large size, and susceptible to electromagnetic interference. To overcome these limitations, photonics-assisted microwave frequency measurement has been proposed, which provides the advantageous features such as instantaneous measurement, large measurement bandwidth, low loss, small size, and immune to electromagnetic interference.

It is known that an optical channelizer can analyze the spectrum of multiple arbitrary optical microwave signals [1]-[3]. The microwave frequency would be instantaneously derived from the measured spectrum. It requires, however, a specially designed diffraction grating and a photodetector (PD) array, making the system bulky and costly. The measurement range and the resolution of the measurement are typically limited to 20 GHz and 1 GHz, respectively.

Incoherent frequency-to-time mapping was also proposed to estimate the frequencies of multiple signals [4], but the measurement resolution is poor or a high speed sampling oscilloscope with a high dynamic range is required.

IFM based on the monitoring of the optical or microwave powers of an optical microwave signal that experience different power penalties is considered a promising solution for instantaneous frequency measurement with a large frequency measurement range (>20 GHz) and a high resolution (<200 MHz) [5]-[14], but the measurement is only accurate for a single-frequency signal. The basic concept of this approach is to measure the optical [5]-[8] or microwave powers [9]-[14] of the optical microwave signal that experience two different power penalties. Based on the power measurement, an amplitude comparison function (ACF) is established. Since the ACF has a unique relationship with the microwave frequency, by estimating the ACF, the microwave frequency is measured.

Since the dynamic range (the ratio of the maximum and the minimum detectable powers) of an IFM receiver cannot be infinite, to obtain a maximized measurement range with almost a uniform measurement resolution, it is highly desirable that the ACF is linear. A linear ACF would also allow an accurate measurement of the center frequency of a pulsed microwave signal. On the other hand, an ACF is also dependent on other parameters of the system, such as the wavelengths of the laser sources, the responsibility of the PDs and the insertion losses of the transmission paths. Practically, a calibration should be performed before the measurement to guarantee a high measurement accuracy. If the ACF is directly proportional to the microwave frequency, calibration only requires a reference microwave signal at a fixed frequency. In

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different ACFs were reported but none of them are directly proportional to the microwave frequency.

In this paper, we propose a novel technique for instantaneous frequency measurement with a maximized measurement range. The resulted ACF is almost directly proportional to the microwave frequency. A proof-of-concept experiment is carried out. In the approach, a key module is a photonic microwave differentiator, which is realized using a polarization modulator (PolM) and an optical bandpass filter (OBPF). A microwave frequency measurement range as large as 25 GHz is demonstrated. The use of the scheme to measure the carrier frequency of a pulsed microwave signal is also investigated.

A linearly polarized continuous-wave (CW) light wave from the LD is fiber coupled to the PolM with its polarization direction oriented at an angle of 45° to a principal axis of the PolM. The microwave signal with its frequency to be measured is applied to the PolM via its RF port. In the approach, a key module is a photonic microwave differentiator, which is realized using a polarization modulator (PolM) and an optical bandpass filter (OBPF). A microwave frequency measurement range as large as 25 GHz is demonstrated. The use of the scheme to measure the carrier frequency of a pulsed microwave signal is also investigated.

The optical field at the output of the PolM can be expressed as

$$ E_x(t) = \sqrt{2} E_0 \exp(j\omega_t t) \left[ \exp\left(\frac{j}{2} \beta \sin \Omega t \right) \right] $$

where $E_0$ and $\omega_t$ are the amplitude and the angular frequency of the input optical field, $\beta$ is the phase modulation index, and $\Omega$ is the angular frequency of the microwave signal. Under a small signal modulation condition, i.e. $J_0(\beta) \approx 1$, (1) can be expanded in terms of Bessel functions of the first kind.

$$ E_x(t) = \sqrt{2} E_0 \exp(j\omega_t t) \left[ 1 + J_1\left(\frac{\beta}{2}\right) e^{i\Omega t} - J_1\left(\frac{\beta}{2}\right) e^{-i\Omega t} \right] $$

where $J_n(x)$ represents the nth-order Bessel functions of the first kind.

The signal expressed in (2) is then split into two branches by a polarization maintaining coupler. In the upper branch, a polarizer with its transmission axis aligned at an angle of 45° to one principal axis of the PolM is inserted. The PolM and the polarizer will be combined to perform intensity modulation [16]. If the optical signal at the output of the polarizer is sent to a PD for square-law detection, the ac term of the photocurrent is

$$ I_i \approx R_i |E_i|^2 J_1\left(\frac{\beta}{2}\right) \sin \Omega t $$

where $R_i$ is a parameter related to the optical loss of the optical path and the responsivity of the PD. In writing (3), we assume that the PolM-based intensity modulator is biased at the quadrature transmission point, which can be implemented by adjusting the PC to introduce a $\pi/2$ phase difference to $E_x(t)$ and $E_y(t)$.

In the lower branch, a second polarizer with its transmission axis aligned with one principal axis of the PolM is employed to select one of the phase modulated signals expressed in (2), e.g., $E_y(t)$. An OBPF is incorporated to perform phase-modulation to intensity-modulation (PM-IM) conversion, with the entire operation equivalent to a first-order microwave differentiator [17]. Assume that the response of the optical filter has two linear slopes and the carrier of the phase modulated signal is located at one of the two slopes, say, the left slope, as shown in Fig. 2. After the OBPF, $E_y(t)$ becomes
where $K$ is the slope ($K > 0$) and $\omega_c$ is the left zero transmission point of the filter. When this signal is detected by a PD, the ac term of the photocurrent is given by

$$I_2 = R_1 |E_1| K^{-1} J_1 (\frac{\beta}{2}) (\omega_c - \omega_l) \Omega \sin \Omega t$$

(5)

The ratio of the two photocurrents in (5) and (3), referred to as the ACF, is given by

$$ACF(f) = \frac{I_2}{I_1} = \frac{R_1}{R_2} K^{-1} (\omega_c - \omega_l) \Omega$$

(6)

where $R_1$ and $R_2$ can be made identical by adjusting the losses of the optical paths via optical attenuators. As can be seen from (6), the ACF is directly proportional to the frequency of the input microwave signal, and is not dependent on the input optical power and the microwave modulation index. Therefore, based on the value of the ACF, we can estimate the frequency of the input signal by the following expression,

$$f = \kappa \cdot ACF$$

(7)

where $\kappa = \frac{1}{2\pi K^{-1} (\omega_c - \omega_l)}$.

It should be noted that $\kappa$ contains the information of the laser wavelength. Therefore, the wavelength drift of the laser source would contribute to the measurement error. For instance, the wavelength of the laser used in our experiment can shift within 5 pm (~600 MHz) in one-hour observation and $\omega_c - \omega_l \approx 40$ GHz, which gives a measurement error of $\Delta f \approx 0.015f$. When $f = 20$ GHz, the measurement error can be 300 MHz. One possible way to reduce the influence of the wavelength drift is to have a large $\omega_c - \omega_l$, or to perform a calibration before the measurement.

A proof-of-concept experiment based on the scheme shown in Fig. 1 is carried out. A light wave at 1549.70 nm emitted from a laser diode is complementarily phase modulated at a 40-Gb/s PolM (Versawave Technologies) by a microwave signal that is generated by a vector network analyzer (VNA, Agilent E8364A, 45 MHz - 50 GHz, IF < 40 kHz). The phase modulated signals are split into two branches by an optical coupler. In the upper branch, PM-IM conversion is performed at a polarization beam splitter (PBS) serving as a polarizer. In the lower branch, one of the phase-modulated signals is selected by another PBS and sent to an OBPF to implement a first-order photonic microwave differentiation. The transmission spectrum of the OBPF is shown in Fig. 3. The left slope from 1549.52 to 1549.91 nm is almost linear. Two 45-GHz PDs are employed to convert the optical signals to electrical signals with the microwave powers measured by the VNA.

Fig. 4(a) shows the detected microwave powers in the upper and lower branches. The input microwave power is set at 0 dBm. Based on (3), the microwave power of the intensity-modulated signal in the upper branch should keep constant, but the experimental curve has large variations and the entire curve is decreasing in the range from 0–25 GHz. These imperfections are mainly resulted from the imperfect performance of the electrical devices used in the experiment.
The variations also present in the curve of the differentiated signal in the lower branch. Therefore, the ratio of the two signals is free from the variations. As can be seen from Fig. 4(a), the ACF is almost directly proportional to the frequency of the input microwave signal, which allows the determination of an unknown input frequency from 0 to 25 GHz. The small nonlinearity is due to the nonlinear slope of the transmission spectrum of the OBPF. To account for the nonlinearity, a more accurate ACF curve is obtained by fitting it using a quadratic polynomial function, which is given as \( \text{ACF} = 5.9 \times 10^{-12} f - 4.19 \times 10^{12} f^2 \). Fig. 4(b) shows the measurement error versus the frequency of the input microwave signal. In the frequency range from 0.5 to 18 GHz, the measurement error is within ±0.2 GHz. The measurement error is increased to ±0.4 GHz in the frequency range from 20 to 25 GHz. Again, this is due to the imperfections of the electrical devices used in the experiment, which have large insertion losses in this frequency range. To reduce the measurement error, an EDFA may be inserted before the PD or an electrical amplifier may be employed after the PD.

Since the ACF is almost linear, the system can be employed to evaluate the carrier frequency of a double-sideband (DSB) pulsed microwave signal. In the experiment, the pulsed microwave signal is generated by mixing a CW microwave signal from a microwave source (Agilent 8254A) with a 500-MHz NRZ signal at an electrical mixer (2–18 GHz). To detect the microwave powers of the received pulses, the signal after the PD is sent to a 0.01 to 26.5 GHz electrical detector followed by a low-pass filter. The two branches are first calibrated using a 10-GHz reference microwave source. Then, the pulsed microwave signal is led to the RF port of the PolM for frequency measurement. The measurement results are shown as the solid squares in Fig. 4(a). When the frequency of the CW microwave signal is tuned from 3 to 18 GHz, the measurement error is within ±0.4 GHz. The measurement results are kept unchanged when the power of the CW microwave signal sent to the mixer decreases from 16 to 10 dBm.

It is important to note that the PolM, optical coupler, polarizers, and OBPF can be integrated in a monolithically chip. As a result, the photonic integrated circuit technology would enhance the performance of the proposed system. The measurement range can be extended if an OBPF with a wideband linear slope is applied.

IV. CONCLUSION

A novel photonic technique for instantaneous microwave frequency measurement with a maximized measurement range has been proposed and demonstrated. The fundamental concept to achieve a maximized frequency measurement range was to achieve a linear ACF, which was obtained by calculating the power ratio of a first-order differentiated signal and an intensity-modulated signal. The differentiation was performed in the system by phase modulation and PM-IM conversion in an OBPF. A measurement range of 0–25 GHz at a resolution of ±0.4 GHz was obtained. The resolution could be further improved by using wideband electrical devices or incorporating amplifiers in the receiver. The scheme was also used to measure the carrier frequency of a pulsed microwave signal. For a measurement range of 3–18 GHz, a measurement resolution of ±0.4 GHz was resulted.

REFERENCES