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Photonic approach to broadband instantaneous microwave frequency measurement with improved accuracy

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ABSTRACT

A photonic approach for instantaneous microwave frequency measurement over a wide bandwidth is proposed and experimentally demonstrated based on the fading effect of the fiber. In this scheme, three lights with different wavelengths and three sections of optical fiber are used to construct the frequency-dependent amplitude comparison functions (ACFs), using a phase modulation along with an intensity modulation. The unknown microwave frequency can be determined from the intersection of three ACFs. The method can not only provide extended measurable range of the microwave frequency, but also improve the accuracy by choosing an ACF with a large slope. The measurement errors as demonstrated in the experimental results are within ± 90 MHz in the frequency range of 0.5–20 GHz.

1. Introduction

In modern radar and other electronic warfare applications, the microwave receiver is required to be capable of estimating the frequency of an unknown microwave signal in a short period of time. Therefore, the instantaneous frequency measurements (IFM) become essential nowadays. The conventional electronic techniques [1–3] for frequency measurement have shown some good property. However, due to the drawbacks such as slow response, limited bandwidth and electromagnetic interference, their applications on wide operating frequency range and real-time response are still limited. Instead, the photonic techniques [1–9] are good alternation with the benefits of large bandwidth, low power consumption, light weight and immunity to electromagnetic interference. In the past few years, a number of photonic approaches in the field of IFM for a wide bandwidth and near-real time have been reported [1–9]. Among them, the IFM system based on the frequency-to-power mapping technique [1,2,4–7] have attracted a lot of attentions. These techniques employ a Mach–Zehnder intensity modulation (MZM) or a phase modulation (PM) to construct one ACF, which is then used to estimate the microwave frequency from a simple microwave power mapping. The measurement range can be adjusted by varying the wavelength space of the light wave or the length of the fiber. However, the measurement error can be enlarged as using a flat ACF curve. Furthermore, the operable bandwidth is still limited to one monotonic region of the ACF at low frequency. In order to overcome these limitations, several ACFs using MZM [8] or PM [9] are built with a large slope. In these approaches, the measurable frequency range extend from 7 GHz to 20 GHz together with improved accuracy less than ± 140 MHz. Although the measurable frequency can be expanded in a certain range, the low frequency end is still difficult to be estimated due to the minimal change of the ACFs.

In this paper, a novel approach for microwave frequency measurement is proposed based on a PM in combination with an intensity modulation (IM), which effectively expands the measurable frequency range without ambiguities. In the system, several frequency-dependent ACFs are jointly utilized to determine the microwave signal frequency employing the output microwave signal power fading effect. In this approach, the measurable frequency range can be extended from 0.5 GHz to 20 GHz, avoiding the lower frequency limitation in traditional techniques. In addition, the accuracy is improved by selecting the proper section of the ACFs with large slope, showing the potential of wide range frequency measurement with high accuracy.

2. Theory

The schematic diagram of the proposed IFM measurement system is shown in Fig. 1. In the measurement system, the unknown microwave signal is split equally into two parts by the electrical power splitter (PS). The light wave with the wavelength of λ_1 is modulated by the first part of the unknown microwave signal, and another two light waves with wavelengths of λ_2 and λ_3

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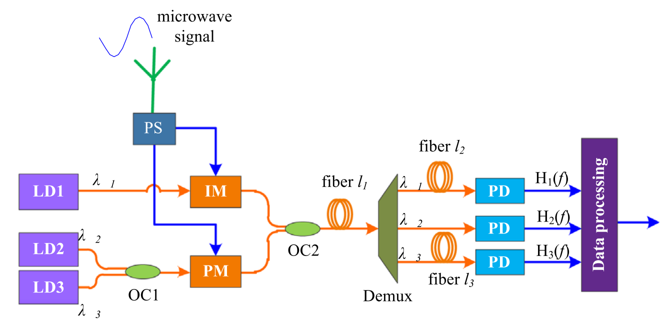

Fig. 1. The schematic diagram of the proposed instantaneous microwave frequency measurement system.

are combined in the first 3 dB optical coupler and modulated by the second part of microwave signal. After combined by the second 3 dB optical coupler, these three modulated optical signals transmitting through the first piece of dispersive fiber l_1 are demultiplexed and the light wave with the wavelength of λ_2 is detected directly. The other two optical wavelengths of λ_1 and λ_3 pass two different dispersive fibers (l_2 and l_3), respectively, and then the optical signals are detected by two photodetectors (PDs). Three detected microwave powers are operated in the data processing unit. In our measurement system, a single microwave frequency input is implemented. Due to the non-monotone of the ACF in the data processing unit, several potential frequency solutions is estimated by the ACFs. In order to obtain the actual frequency, the algorithm searches all solutions of each ACF, and selects the intersection of potential frequencies of different ACFs, which is unique. By using several ACFs with large slope and a simple search algorithm, the proposed IFM approach of determining the unknown microwave frequency overcomes the limitation imposed by a single monotonic interval of one ACF.

Because of the chromatic dispersion of the fiber, the detected microwave powers experience the power fading effect. The transmission functions after PDs can be expressed as [1,4]:

$$H_1=\gamma_1\cos^2\left(\frac{\pi D_1 l_1\lambda_1^2 f^2}{c}\right)$$
$$H_n=\gamma_n\sin^2\left(\frac{\pi D_n l_n\lambda_n^2 f^2}{c}\right)\quad (n=2,3)\qquad(1)$$

where H_1 is the intensity modulated optical dual-sideband signal with the wavelength of λ_1, while H_n is the phase modulated optical signals with the wavelengths of λ_2 and λ_3, respectively. In Eq. (1), γ_i ($i=1, 2, 3$) represents the total response coefficient of the link related to the optical power, modulation index, response of the PD and the insertion loss of the photonic link, D_i (i=1, 2, 3) is the chromatic dispersion coefficient of single mode fiber (SMF)in ps/(nm km), L_i ($i=1, 2, 3$) is the length of the SMF, λ_i ($i=1, 2, 3$) is the wavelength of the light wave, f is the microwave frequency, c is the light velocity in the vacuum.

Through the detected microwave powers of three photonic links, three ACFs in dB with the ratio of the microwave powers can be constructed, which are expressed in Eq. (2) [1,4]

$$\begin{cases}\mathrm{ACF}_{12}=10\log\frac{H_1}{H_2}=20\log\dfrac{\cos\left(\frac{\pi D_1 l_1\lambda_1^2 f^2}{c}\right)}{\sin\left(\frac{\pi D_2 l_2\lambda_2^2 f^2}{c}\right)}+\alpha_1\\ \mathrm{ACF}_{23}=10\log\frac{H_2}{H_3}=20\log\dfrac{\sin\left(\frac{\pi D_2 l_2\lambda_2^2 f^2}{c}\right)}{\sin\left(\frac{\pi D_3 l_3\lambda_3^2 f^2}{c}\right)}+\alpha_2\\ \mathrm{ACF}_{31}=10\log\frac{H_3}{H_1}=20\log\dfrac{\sin\left(\frac{\pi D_3 l_3\lambda_3^2 f^2}{c}\right)}{\cos\left(\frac{\pi D_1 l_1\lambda_1^2 f^2}{c}\right)}+\alpha_3\end{cases}\qquad(2)$$

where $\alpha_i=10\log\gamma_i/\gamma_j (i=1, 2, 3; j=2, 3, 1)$ is the ratio of the different links. Each ACF is utilized to acquire multi-frequency with a few ambiguous frequency sections due to the several monotone intervals in the measurement range. The algorithm is used to search all the probable solutions of each ACF and optimal design of the wavelengths and the fiber lengths, and the ultimate frequency is obtained by selecting the intersection of potential solutions of different ACFs. Thus, the measurable frequency range can be extended, without restricting to the frequencies where the ACF is monotonic.

To achieve the desired results, the main parameters of the IFM measurement system, e.g. the wavelengths and the fiber lengths, should be designed carefully. To utilizable, the wavelength of three LDs should be fitted. In addition, the fiber length should also be chosen carefully. As a result, the monotonic regions of three ACFs can be interleaved to expand the measurable frequency range. By optimizing the wavelengths and the fiber lengths, the unique frequency can be determined. According to Eq. (2), the relationship between ACFs and the frequencies are shown in Fig. 2. The normalized ACF_{12}, ACF_{31},ACF_{23} are obtained with the parameters of $\lambda_1=1605$ nm, $\lambda_2=1525$ nm and $\lambda_3=1550$ nm, three pieces of fiber lengths with $l_1=25$ km and $l_2=l_3=15$ km, $D_1=19.52$ ps/(nm km) @1605 nm, $D_2=15.02$ ps/(nm km) @1525 nm and $D_3=16.43$ ps/(nm km) @1550 nm [10,11], and $\alpha_1=\alpha_2=\alpha_3=0$. As shown in the Fig. 2, it can be seen that each ACF is multivalued for the behavior of dispersion induced power fading effect.

When an unknown microwave signal is received by the antenna, the algorithm for the microwave frequency in the data processing unit is described as shown in Fig. 2. Firstly, the values of the ACF_{12}, ACF_{23} and ACF_{31} can be calculated as 17.25 dB, −4.07 dB and −13.22 dB after detecting by the PDs. Then, the algorithm searches all the potential solutions of each ACF. Hence, the probable microwave frequencies utilizing the ACF_{12} of 17.25 dB are 3.81 GHz, 18.135 GHz and 18.91 GHz. Based on the ACF_{23} of −4.07 dB, the possible frequency is 16.83 GHz, ignoring the flat frequency section from 1 GHz to 12 GHz. The probable frequencies are 3.81 GHz, 14.25 GHz and 14.94 GHz determined by the ACF_{31} of −13.22 dB. The actual frequency can be determined from the intersection of probable microwave frequencies of three ACFs. To improve the measurement accuracy, the ACF_{12} is used to estimate the frequency of the unknown input microwave signal due to the larger slope around 4 GHz, compared with the other two. Therefore, the practical frequency can be obtained as 3.81 GHz. As the same, ACF_{23} or ACF_{31} can also be used in the other frequency range where the slope is large.

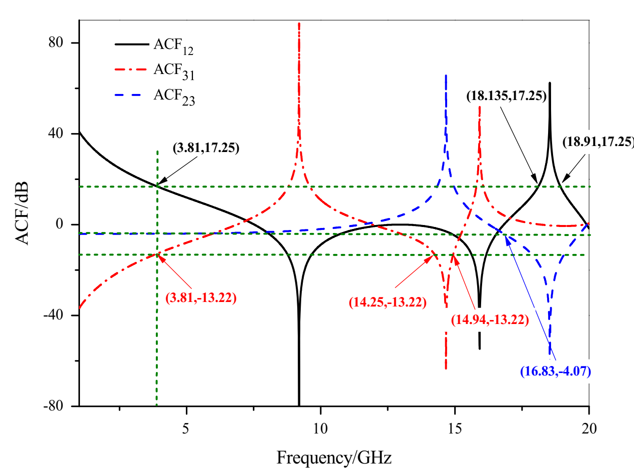

Fig. 2. Frequency estimation with ACFs from the power variation response.