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Performance analysis on an instantaneous microwave frequency measurement with tunable range and resolution based on a single laser source

Jing Li [a,b], TiGang Ning [a,b], Li Pei [a,b,*], Wei Jian [a,b], Jingjing Zheng [a,b], Haidong You [a,b,c], Hongyao Chen [a,b], Chan Zhang [a,b]

[a] Key Laboratory of All Optical Network & Advanced Telecommunication Network of EMC, Beijing Jiaotong University, Beijing 100044, China
[b] Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China
[c] Science and Information College, Qingdao Agricultural University, Qingdao 266109, Shandong, China

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ABSTRACT

A prototype of instantaneous microwave frequency measurement with tunable range and resolution based on a single laser source is proposed and analyzed. In the proposal, one polarization modulator (PolM) followed by a section of dispersion compensating fiber (DCF), a polarization beam splitter (PBS) and two photodiodes (PDs) are used as the key component. To obtain an amplitude comparison function (ACF), the lightwave from a laser source should be first oriented at an angle of α ($\alpha \neq 0^\circ$ or 90°) relative to one principal axis of PolM. After transmission of DCF, the PBS is connected with principal axis $\pm 45^\circ$ to that of PolM. Then, by monitoring and processing the microwave power of two optical paths via two PDs, frequency of microwave signal can be easily estimated. It is found that the measurement range can be stretched by simply adjusting α. Its performance is first analyzed by theory and then verified by simulations. Since the proposal is characteristic with its tunable measurement range and resolution, a frequency measurement range as large as 13.2 GHz with a measurement resolution of ± 0.15 GHz is obtained.

1. Introduction

Photonic instantaneous microwave frequency measurement (IFM) has been a topic of interest over the past few years. One typical photonic IFM owns many advantages, such as high bandwidth, low loss, and immunity to electro-magnetic interference (EMI) [1,2], over a conventional electronic system. Due to its inherent advantages, IFM can find many applications, one of which is in the field of electronic warfare (EW). Normally, the unknown microwave signal is required to be frequency identified before sent to the second level receiver for further processing. Thus it is of great importance to identify the frequency of a specially intercepted microwave signal from radar or communication. Recently, various techniques have been proposed to implement photonic IFM. For example, the IFM can be realized by using a coherent optical RF channelizer [3,4], complementary optical filter [5–7], and dispersion-induced power-fading functions [8–17]. For all photonic IFM, the following two characteristics should be met: 1) a wide measurement range to satisfy application with frequency from few hundreds of megaHertz to hundreds of giga-Hertz; 2) a high measurement resolution in order to avoid error frequency identification. It is found that the approaches in [8–17], which is based on the monitoring of the microwave power of an optical microwave signal that experiences different power penalties, is a promising solution for IFM with a large frequency measurement range and a relatively high resolution. However, for most cases [8–12], the measurement range and resolution are fixed for a given system, which is not desirable for EW applications requiring a specific measurement range and a high resolution. Typically, the measurement range and resolution are two complementary features which cannot be satisfied simultaneously, which means that a higher measurement resolution results in a smaller measurement range. To solve this problem, the major task is to stretch the measurement range without degrading the resolution. Therefore, many researches focus on an IFM system with tunable measurement range and resolution [13–17]. For example, it can be realized by applying adjustable dispersion via tuning two optical wavelength with a large wavelength spacing [13]. But the tuning range is limited to few giga-Hertz due to the relatively small dispersion changes resulting from the wavelength tuning. Then in [14], one single laser source incorporating a dual-output Mach–Zehnder modulator is

* Corresponding author at: Key Laboratory of All Optical Network & Advanced Telecommunication Network of EMC, Beijing Jiaotong University, Beijing 100044, China.
E-mail address: lipei@bjtu.edu.cn (L. Pei).

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employed. By tuning the laser's wavelength, the measurement range can be extended. But the scheme still requires a huge wavelength tuning so as to reach a relatively higher dispersion changes. In [15], a reconfigurable IFM system based on a dual-parallel Mach Zehnder modulator and a Mach–Zehnder modulator is proposed. According to the research, the measurement range can be tuned by adjusting laser wavelength or bias voltage. But the approach will suffer from the bias drift problem. In [16], the same group proposed an IFM system based on stimulated Brillouin scattering. By varying the reference driving frequency, the measurement range as well as the resolution can be tuned. But the scheme still suffers from bias drift problem and a relatively complex architecture. In [17], an IFM system based on a polarization modulator is proposed. By simply adjusting the polarization angle, the measurement range as well as the resolution can be tuned. But the scheme requires two laser sources with equal power and a large wavelength spacing so as to provide enough dispersion and an optical filter to separate lightwaves, which might be costful and complex in architecture.

In this work, we report a simplified IFM system with tunable measurement range and resolution. The key component is a polarization modulator (PolM) followed by 2 km dispersion compensating fiber (DCF), a polarization beam splitter (PBS) and two photodiodes (PDs). By monitoring the microwave power, a monotonically decreasing amplitude comparison function (ACF) can be obtained. Since the ACF is dependent on the polarization angle of incident light α, the measurement range of the proposed IFM system can be stretched by simply adjusting α. It is found that bias drift (within $-20\sim20\%$) has little impact on the range and resolution. The key significances associated with our proposal are the single-wavelength operation and filter-less architecture, which will simplify the IFM system a lot when compared with previous reported approaches [13–17].

2. Model and theory

Fig. 1 shows the schematic setup of the proposed IFM with tunable range. The lightwave from the continuous-wave (CW) laser is first coupled to the polarization modulator (PolM). The key component, PolM, can be considered as a special phase modulator that supports transverse electric (TE) and transverse magnetic (TM) modes with complementary phase modulation indices. The polarization controller (PC1) is used to align the incident light to make sure that its polarization direction is 45° relative to one principal axis of the PolM ($\hat{y}$). Supposing that the unknown microwave signal is $V_{RF}(t)=V_{RF}\sin\Omega t$, where V_{RF} and $\Omega=2\pi f_{RF}$ denote the magnitude and angular frequency, respectively. Then the output optical field after PolM can be expressed as follows:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} \propto E_0 e^{j\omega_0 t}\begin{bmatrix} \sin\alpha\exp(jm\cdot\sin\Omega t+j\varphi) \\ \cos\alpha\exp(-jm\cdot\sin\Omega t) \end{bmatrix} \quad (1)$$

where E_0 is magnitude of optical carrier, ω_0 is angular frequency of optical carrier, $\varphi=\pi V_{bias}/V_\pi$ is the bias-induced phase shift, and $m=\pi V_{RF}/\sqrt{2}V_\pi$ is modulation index, where V_π denotes half-wave voltage of the PolM. Under small signal modulation, Eq. (1) can be simply concluded as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = E_0 e^{j\omega_0 t}\begin{bmatrix} \sum_{n=-1}^{1}\sin\alpha J_n(m)\exp(jn\Omega t+j\varphi) \\ \sum_{n=-1}^{1}\cos\alpha J_n(-m)\exp(jn\Omega t) \end{bmatrix} \quad (2)$$

where J_n is the Bessel function of the first kind of order n. The signal in Eq. (2) is then launched into a spool of 2 km DCF ($D=-160$ ps/km nm). Since the DCF we use is only 2 km in length, the walk off effect between two orthogonal polarized light paths is negligible. The transmission function of the DCF is similar to that of the single mode fiber [18,19]. It can be expressed as (neglecting the constant phase and higher order terms)

$$H(\omega)=\exp\left[-j\frac{\lambda_0^2 DL}{4\pi c}(\omega-\omega_0)^2\right] \quad (3)$$

where λ_0 is the optical wavelength, c is the speed of light in vacuum, L is fiber length and D is chromatic dispersion parameter. The optical field after the DCF becomes

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = E_0 e^{j\omega_0 t}\begin{bmatrix} \sum_{n=-1}^{1}\sin\alpha J_n(m)\exp(jn\Omega t+j\varphi_n+j\varphi) \\ \sum_{n=-1}^{1}\cos\alpha(-1)^n J_n(m)\exp(jn\Omega t+j\varphi_n) \end{bmatrix} \quad (4)$$

where $\varphi_n=-n^2\lambda_0^2 DL\Omega^2/4\pi c$ is dispersion-induced phase shift.

A polarization beam splitter (PBS) is then connected with the DCF via PC2 with principal axis $\pm45°$ to that of the PolM, as shown in Fig. 1. The two ports (Port 1 and Port 2) correspond to two complementary output transfer functions [20]. Tuning the bias voltage of the PolM to let $\varphi=90°$, Eqs. (5) and (6) show the detail expression of optical signals at Port 1 and Port 2:

$$E_{Port1}(t)=\frac{\sqrt{2}}{2}E_0 e^{j\omega_0 t}\sum_{n=-1}^{1}\left[j\sin\alpha +(-1)^n\cos\alpha\right]J_n(m)\exp(jn\Omega t+j\varphi_n) \quad (5)$$

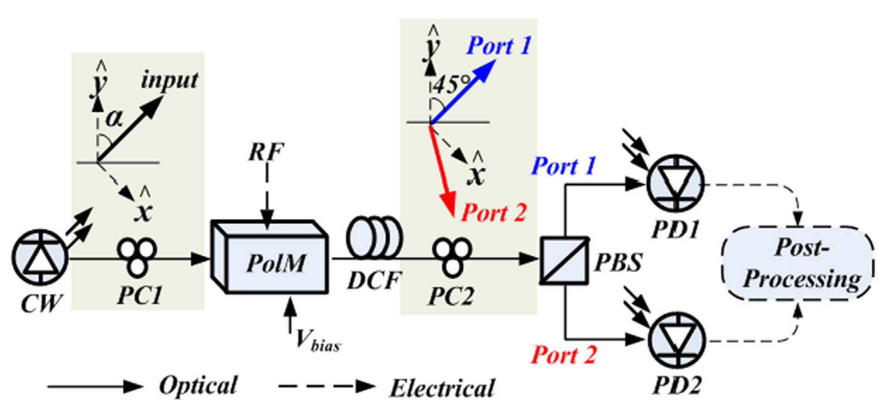

Fig. 1. Schematic setup of the proposed IFM with tunable range (CW—continuous wave; PC—polarization controller; RF—radio frequency; PolM—polarization modulator; fiber; PBS—polarization beam splitter; DCF—dispersion compensating fiber; PD—photodiode).