Research Article | Vol. 28, No. 25 / 7 December 2020 / Optics Express 37353
Optics EXPRESS

Instantaneous microwave frequency measurement using few-mode fiber-based microwave photonic filters

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Abstract: Instantaneous frequency measurement (IFM) of microwave signals using photonic methods provides a novel and efficient approach for fast and broadband radio frequency (RF) signal analysis. Here, we propose and experimentally demonstrate a photonic-assisted IFM method utilizing a few-mode fiber-based microwave photonic technique. By offset splicing the few-mode fiber (FMF) with a single mode fiber, both LP01 and LP11 modes can be excited, which is used to develop a microwave photonic filter (MPF). A detailed analysis of the FMF as the true time delay line is presented. An amplitude comparison function (ACF) that is the ratio of frequency response traces of an MPF pair is established, which is used to determine the unknown microwave frequency instantaneously. The proof-of-concept experiment demonstrates a frequency measurement range of 0.5 GHz to 17.5 GHz and a measurement accuracy of ±0.2 GHz in most of the frequency points. The proposed system has the merits of simplicity, cost-effectiveness, compactness and robustness.

1. Introduction

Instantaneous frequency measurement (IFM) of unknown microwave signals plays an important role in many modern applications, including electronic warfare and electronic intelligence systems [1,2]. These applications require fast and accurate measurement of the microwave frequency with large dynamic range. However, the conventional electrical IFM approaches have the limitation on the frequency measurement range due to the bandwidth-limited electronic components, and are vulnerable to the electro-magnetic interference (EMI). To overcome this electronic bottleneck, microwave photonic technologies are recently developed to achieve IFM systems [3–6]. Compared with the electronic methods, these photonic-assisted IFM approaches have the advantages of large frequency measurement range, low loss, small size, and immunity to EMI, etc.

In a photonic-assisted IFM system, a relationship between the microwave frequency and some specific parameters of the microwave photonic subsystem should be established, thus we can obtain the microwave frequency through monitoring these parameters. Generally, these parameters could be the microwave power, the optical power, and the time delay [7–18], etc. In the IFM systems based on microwave power monitoring, the target microwave frequency is mapped to the detected microwave power or its variation. The key is to find suitable system frequency responses, which changes monotonically [7–11]. On the other hand, in the optical power monitoring based IFM systems, the target microwave frequency is converted to the optical power or its variation. The critical component in these schemes is an optical filter with specific

#410847 https://doi.org/10.1364/OE.410847
Journal © 2020 Received 25 Sep 2020; revised 20 Oct 2020; accepted 21 Oct 2020; published 24 Nov 2020

spectral response. The system can be implemented using special modulation method (e.g. carrier suppressed double side band modulation) with matched laser wavelength; as a result, the optical power can change monotonically with the microwave frequency within the measurement range [12–16]. Additionally, frequency-to-time mapping method has also been proposed for IFM systems, where the electrical time delay due to the frequency changing can be directly measured through the oscilloscope, and it can measure multiple frequencies simultaneously [17,18].

As for the microwave power monitoring based IFM method, a widely employed strategy is to develop a microwave photonics filter (MPF) based measurement system. In recent years, aiming at expanding the transmission capacity of optical fiber communication system, few-mode fiber-based space-division multiplexing technique has been intensively investigated [19–21]. It is realized that FMF has also shown great potential in the applications of microwave photonics techniques, e.g. achieving the true time delay lines (TTDLs) by exploiting the transmission time delays between the spatial modes of an FMF [22,23]. Thanks to the mode division multiplexing transmission capability of FMF, the traditional implementation way of optical delay lines that use multiple single mode fibers (SMFs) in finite impulse response (FIR) microwave photonic filters is substituted, which considerably simplifies the system composition. FMF-based microwave photonics links have the merits of simple structure, compactness, robust and performance versatility, etc. However, the unique performance of FMF has not been explored to achieve IFM system yet.

In this paper, we propose and experimentally demonstrate a photonic-assisted IFM system utilizing FMF-based microwave photonic filters, for the first time to the best of our knowledge. In the proposed IFM approach, two separate laser wavelengths are used, which are modulated by an intensity modulator and a phase modulator, respectively. An amplitude comparison function (ACF) that is the ratio of frequency response traces of two microwave photonic filters can therefore be achieved, and eventually the target microwave frequency can be retrieved with the ratio of two detected microwave powers. Since the light is modulated by the intensity and phase modulators, the pair of microwave photonic filters generate different lowpass and bandpass frequency responses, as a result, larger curve slope of the ACF can be obtained, which will help to enhance the measurement resolution significantly. A theoretical analysis of the photonic-assisted IFM and the detail of the FMF-based optical TTDL are presented. To verify the theory, a proof-of-concept experiment has been carried out. A measurement range of 0.5 GHz to 17.5 GHz and a measurement accuracy of ±0.2 GHz in most of the frequency points are achieved using the proposed IFM system.

2. IFM working principle

The schematic diagram of the proposed photonic-assisted IFM scheme with few-mode fiber is shown in Fig. 1. With a certain length of FMF, remote microwave frequency measurement can be realized between base station and remote antenna unit. In the base station, the lightwaves from two CW lasers with different wavelengths are combined and transmitted to the remote antenna unit through single mode fiber (SMF). In the remote unit separated by the wavelength division multiplexing (WDM) filter, the two lightwaves are sent to a Mach-Zehnder modulator (MZM) and a phase modulator (PM) respectively, and modulated by the same unknown microwave signal received from antenna. Then they are combined again and transmitted back to the base station through the FMF. The relative time delay between the two modes (i.e. LP01 and LP11) in FMF helps construct a microwave photonic filter for each of the two wavelength-links. Finally, the modulated lightwaves of two wavelengths are separated again by the WDM filter and detected by a pair of photodiodes (PDs) in the base station. Due to the respective intensity modulation and phase modulation of the two microwave photonic links with different wavelengths, complementary lowpass and bandpass filtering responses are obtained for the two links. The ACF is generated

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by comparing the measured electrical powers from the PDs, which determines the microwave frequency to be measured.

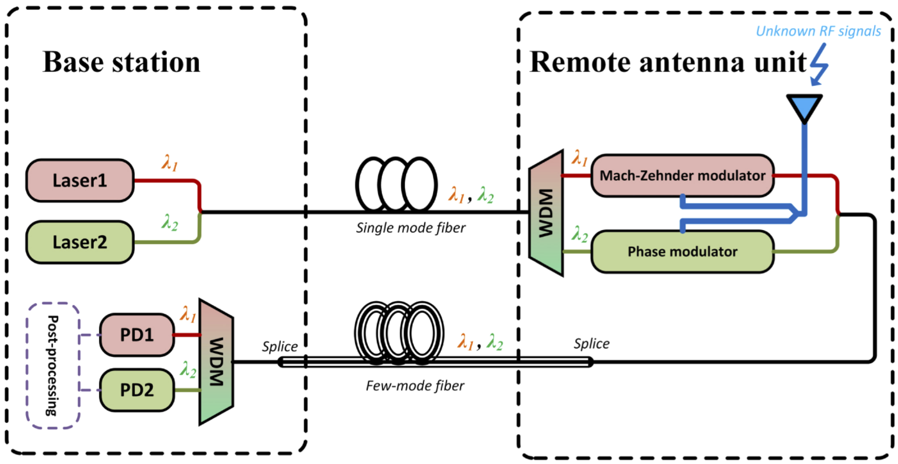

Fig. 1. General schematic of the proposed photonic-assisted instantaneous microwave frequency measurement scheme using few-mode fiber.

Let us consider that the first lightwave $E_1(t) = E_{10}cos(2\pi f_1 t)$ is modulated with MZM, and the second lightwave $E_2(t) = E_{20}cos(2\pi f_2 t)$ is modulated with PM, both by the same RF signal $V_{RF}(t) = V_{RF}cos(2\pi f_{RF} t)$, where E_{10} and E_{20} are the scalar amplitudes, f_1 and f_2 are the optical frequencies of the two wavelengths, V_{RF} and f_{RF} are the voltage and frequency of the microwave signal to be measured. When the MZM is biased at the quadrature point, with small signal modulation model, the electrical fields at the output of MZM and PM can be expressed as

$$E_{IM}(t) = \frac{\sqrt{2}}{2} E_{10}\{J_0(\beta_1)\cos(2\pi f_1 t) - J_1(\beta_1)[\cos(2\pi(f_1 - f_{RF})t) + \cos(2\pi(f_1 + f_{RF})t)]\} \quad (1)$$

$$E_{PM}(t) = E_{20}\{J_0(\beta_2)\cos(2\pi f_2 t) - J_1(\beta_2)[\cos(2\pi(f_2 - f_{RF})t) - \cos(2\pi(f_2 + f_{RF})t)]\} \quad (2)$$

where $J_k(\cdot)$ is the k-th order Bessel function of the first kind, β_1 and β_2 are modulation indices of MZM and PM respectively [24]. After transmission through the FMF, a similar time delay is introduced to the two wavelength-links due to the differential group delay (DGD) between LP01 and LP11 modes, which lead to two power penalty functions (i.e. two filtering frequency responses). Neglecting very weak high-order modes, we actually implement a microwave photonic lowpass filter for the first link with intensity modulation, and another microwave photonic bandpass filter for the second link with phase modulation [25,26]. The two frequency responses are complementary for increasing the slope of the ACF, so higher frequency measurement resolution of the IFM system can be achieved.

At the outputs of the PDs, the electrical powers for the intensity-modulated and the phase-modulated links can be written as

$$P_{IM}(f) = \Re_1 \alpha_1 E_{10}^2 J_0^2(\beta_1) J_1^2(\beta_1) \cos^2(\pi f_{RF} \Delta\tau_1) \quad (3)$$

$$P_{PM}(f) = 2\Re_2 \alpha_2 E_{20}^2 J_0^2(\beta_2) J_1^2(\beta_2) \sin^2(\pi f_{RF} \Delta\tau_2) \quad (4)$$

where $\Re_1$ and $\Re_2$ are the responsivities of the two PDs, α_1 and α_2 show the losses of the two wavelength-links, $\Delta\tau_1$ and $\Delta\tau_2$ are the time delays caused by the two modes in FMF at different

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wavelengths. Considering both the intermodal dispersion and chromatic dispersion, $\Delta\tau$ can be described as

$$\Delta\tau(\lambda) = [(\tau_{11}(\lambda_0) - \tau_{01}(\lambda_0)) + (D_{11}(\lambda_0) - D_{01}(\lambda_0))(\lambda - \lambda_0)] \cdot L \tag{5}$$

where L is the length of the FMF, $(\tau_{11}(\lambda_0) - \tau_{01}(\lambda_0))$ and $(D_{11}(\lambda_0) - D_{01}(\lambda_0))$ show the differential group delay and differential chromatic dispersion between LP01 and LP11 modes around an anchor wavelength λ_0, respectively [22]. Compared with the differential group delay due to intermodal dispersion, the differential chromatic dispersion between the two modes is very small. Thus, the difference between $\Delta\tau_1$ and $\Delta\tau_2$ is tiny and can be neglected in most cases, which means the two microwave photonic filters have similar free spectral ranges (FSRs).

According to the definition of ACF, it is obtained by calculating the ratio of the two detected powers at the PDs, as governed by

$$ACF = \frac{P_{PM}(f)}{P_{IM}(f)} = \frac{2\Re_2\alpha_2 E_{20}^2 J_0^2(\beta_2) J_1^2(\beta_2)\sin^2(\pi f_{RF}\Delta\tau_2)}{\Re_1\alpha_1 E_{10}^2 J_0^2(\beta_1) J_1^2(\beta_1)\cos^2(\pi f_{RF}\Delta\tau_1)} \tag{6}$$

Through link calibration and post-processing, the two links can be normalized. Neglecting the coefficients irrelative to the microwave frequency of the two links, the ACF can be further simplified as

$$ACF = \frac{\sin^2(\pi f_{RF}\Delta\tau_2)}{\cos^2(\pi f_{RF}\Delta\tau_1)} \tag{7}$$

Considering the similarity of $\Delta\tau_1$ and $\Delta\tau_2$, within a certain frequency range, the relationship between the ACF and the microwave frequency is monotonic. Thus, the unknown microwave frequency can be determined by the ACF, i.e. the ratio of the two detected microwave powers. The proposed IFM has a high resolution due to the complementary frequency responses. The measurement frequency range can be increased by using a short FMF.

3. Few-mode fiber characterization

The few-mode fiber used in this experiment is a two-mode fiber with a core diameter of 16.35 um, which supports LP01 mode and LP11 mode. It is a grade-index fiber, whose refractive index profile is shown in Fig. 2(a). The electric field distribution profiles of modes of the FMF have also been simulated using COMSOL Multiphysics. Figures 2(b) and 2(c) present the simulated field distribution of LP01 mode and LP11 mode, respectively. In the experiment, we use an FMF of 70 m length. Around 1550 nm, the differential group delay between LP01 and LP11, i.e. $(\tau_{11}(1550nm) - \tau_{01}(1550nm))$, is 0.391 ps/m, and the chromatic dispersion values for LP01 and LP11 modes are 21 ps/nm/km and 26 ps/nm/km, respectively. Due to this differential time delay between the two modes in FMF, a microwave photonic filter for each of the two wavelength-links will be implemented in our proposed IFM. Thanks to this integrated microwave photonics link configuration, the implementation of system turns out to be quite simple and robust.

In order to excite LP11 mode in the FMF, offset splicing is adopted between the SMF and FMF. To ensure that the power distribution is uniform between LP01 mode and LP11 mode, the optical interference spectrum of the FMF-based modal interferometer is observed in real time during the fiber alignment process, and two fusion splicers working in manual mode are used to adjust the offset between the SMF and FMF. The fiber link is connected to a broadband light source and an optical spectrum analyzer at the two ends to enable the real-time monitoring of the interference spectrum. The optimization of fiber offset is achieved when the extinction ratio of the interference spectrum reaches the maximum. Figure 3(a) shows the splicing region between SMF and FMF with slight offset alignment, and Fig. 3(b) is the measured interference spectrum of the FMF-based modal interferometer, which is formed by the interference between LP01 mode and LP11 mode. The maximum extinction ratio is about 11.5 dB.

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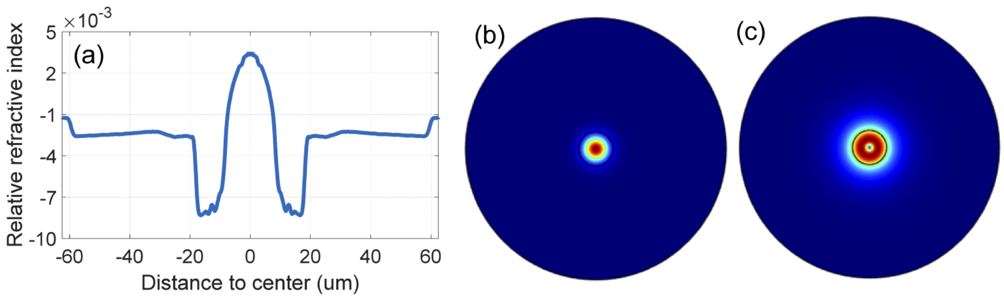

Fig. 2. (a) Refractive index profile of the 2-mode FMF that is used in this experiment; (b) and (c) are the simulated electric field distributions of LP01 mode and LP11 mode, respectively.

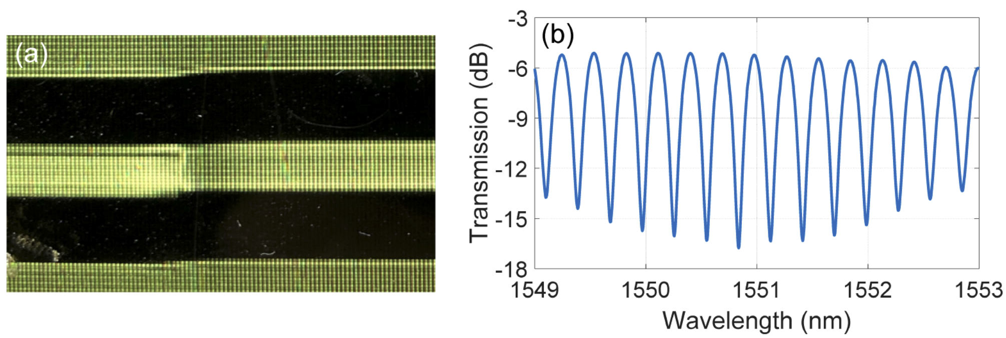

Fig. 3. (a) Offset splicing between the SMF and FMF so as to excite LP11 mode; (b) the optical interference spectrum of the FMF-based modal interferometer that takes place between LP01 mode and LP11 mode.

Owing to the offset splicing between the SMF and FMF, both LP01 and LP11 modes can be excited in FMF, as shown in Fig. 4. Since there are intermodal dispersion and chromatic dispersion that cause differential group delay and differential chromatic dispersion between the modes, it leads to a time delay at the output of FMF. In this way, a compact and robust few-mode fiber transmission links with certain time delay is obtained, which can be used to develop an FMF-based microwave photonics filter.

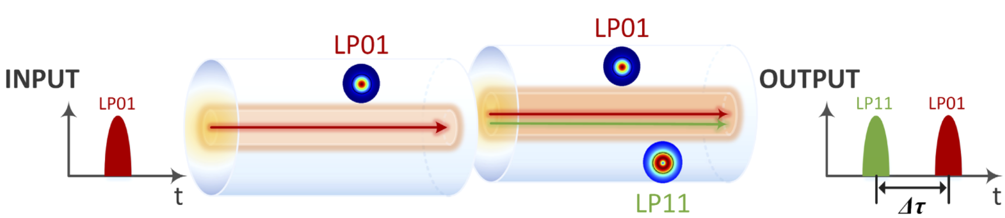

Fig. 4. Schematic diagram of the proposed few-mode fiber based true time delay line, where LP11 mode can be excited due to offset splicing, and a differential delay of $\Delta\tau$ will be generated between the modes.

It is worth mentioning that the FSRs of the microwave photonic filter pair determines the frequency range of the measurement, which is also determined by the time delay between the two modes. With larger FSR, we can obtain wider measurement frequency range. This FSR can be estimated from the optical interference spectrum during the fiber alignment process. The optical

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free spectral range of the FMF modal interferometer is governed by $\lambda^2/\Delta n_{eff}L$, where λ is the wavelength of incident light, Δn_{eff} is the effective refractive index difference of modes, and L is the length of FMF. With the 70 m FMF used in the experiment, the optical free spectral range of the FMF modal interferometer is 0.288 nm around 1550 nm, as shown in Fig. 3(b).

4. Experiment and discussion

The experimental setup of the proposed few-mode fiber-based IFM system is shown in Fig. 5. Two low-coherence light sources with different output wavelengths (i.e. 1550.1 nm and 1552.2 nm) are used, which are modulated by an MZM and a PM, respectively. The 3-dB bandwidth of the two modulators is 25 GHz. After transmitting through a 70 m few-mode fiber, the two signals are separated using a WDM filter, and detected by two 40 GHz photodetectors, respectively. Eventually two microwave power meters are used to detect the microwave powers from the two photodetectors. By calculating the ratio of the two power values, the frequency of the microwave generator can be obtained.

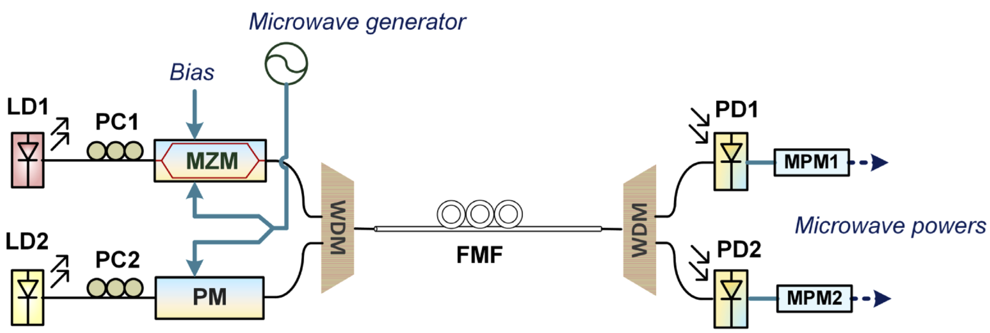

Fig. 5. The experimental setup of the proposed few-mode fiber-based IFM system. LD1 and LD2 are the laser diodes, PC1 and PC2 are the polarization controllers, MZM is the Mach-Zehnder intensity modulator, PM is the phase modulator, WDM is the wavelength-division multiplexing filter, PD1 and PD2 are the photodetectors, MPM1 and MPM2 are the microwave power meters.

In the experiment, we firstly measure the frequency responses of the two microwave filters with a vector network analyzer (VNA, Keysight N5227A), with the input microwave power setting at 10 dBm. The measured normalized frequency responses of two MPFs with intensity modulation and phase modulation are shown in Fig. 6(a). Their power ratio is calculated as the amplitude comparison function, as shown in Fig. 6(b). According to Eq. (5) and using the fiber parameters given in Section 3, the time delay between the two modes for both the 1550.1 nm link and 1552.2 nm link are 27.4 ps and 28.1 ps, respectively, which determines that the FSRs of the MPF pair are 36.5 GHz and 35.6 GHz, respectively. As shown in Fig. 6, the small difference between two FSR values takes no effect in our IFM operation. It is realized that the frequency response curve with intensity modulation is relatively flat at low frequencies, but the curve obtained using phase modulation is relatively flat at high frequencies. When the power ratio of the two curves is used as the ACF, we can get better performance of the IFM for the unknown microwave signal, since large slope can be obtained at both low and high frequencies, which will help to enhance the measurement resolution significantly [27]. Once the ACF is obtained, the target microwave frequency can be retrieved using the ratio of two detected microwave powers by comparing with the established ACF curve. It is worth noting that the measured ACF is more reliable than the calculated value to determine the unknown frequency in a practical application, since it takes account of all the factors of the two wavelength-links. The frequency range of measurement is determined by the monotonic interval of the ACF as shown in Fig. 6(b), which is 18.2 GHz in this case.

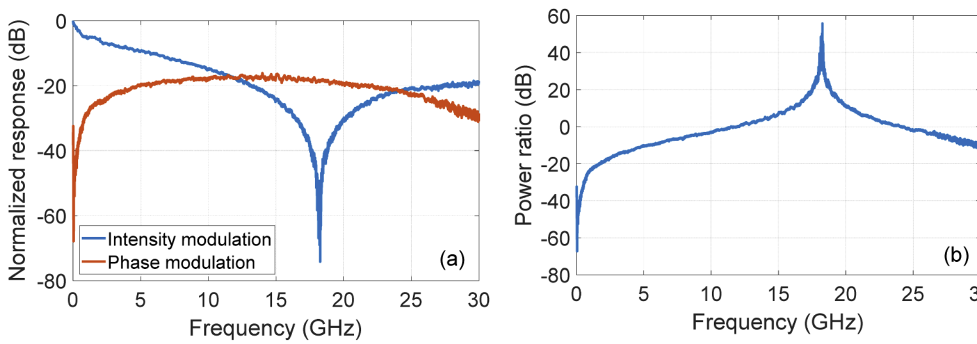

Fig. 6. (a) The measured normalized frequency responses of the microwave photonics filters with intensity modulation and phase modulation, respectively. (b) the measured amplitude comparison function which is the power ratio of the two MPFs.

In order to investigate the performance of instantaneous frequency measurement of unknown microwave signals, a microwave generator (Keysight E8257D) has been used to drive the two modulators with the applied microwave frequency tuned from 0.5 GHz to 18 GHz with a step of 500MHz, and the output microwave powers from the two photodetectors are measured respectively for each applied microwave frequency. Their power ratio is calculated and then compared with the established ACF curve, so that the microwave frequency can be determined immediately. Figure 7(a) shows the retrieved frequency as a function of applied microwave frequency, where good agreement can be observed. The measurement errors between the retrieved frequency and the applied frequency have been calculated and presented in Fig. 7(b). It shows that the error is generally within the range of ±0.2 GHz, except for some high frequency points. The large error may be due to the bad signal-to-noise ratio at high frequencies. In addition, the system instability, e.g. the notch jitter of the microwave photonic filter, might also contribute to this measurement error. It is worth mentioning that the used input microwave power is 10 dBm in this experiment of error evaluation measurement. Since it has been demonstrated in previous investigations that the measurement error is not sensitive to the input microwave power [9,12,27], which can also be inferred from Eq. (7), the performance of system in terms of measurement error and operating frequency won't be affected by the microwave power level.

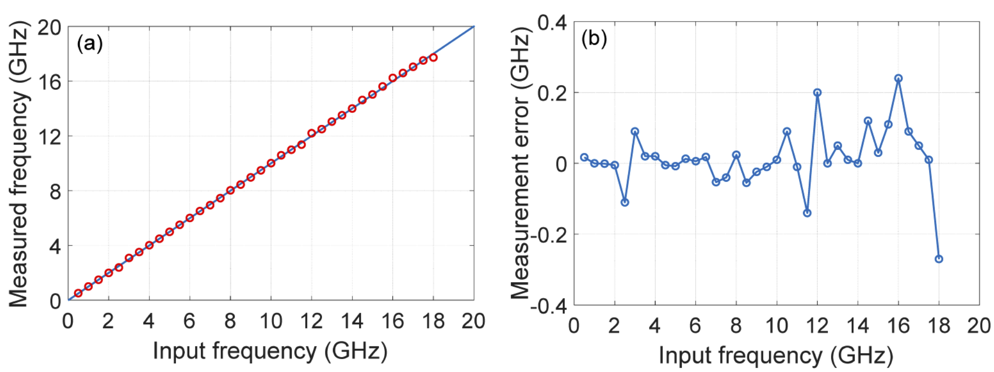

Fig. 7. (a) The retrieved frequency as a function of applied microwave frequency. (b) the measurement error between the retrieved frequency and the applied frequency.

5. Conclusion

In this paper, we propose and experimentally demonstrate a few-mode fiber-based instantaneous frequency measurement approach. By offset splicing the few-mode fiber with single mode fiber, both LP01 and LP11 modes can be excited, which gives rise to time delay after transmission through the fiber, so a true time delay line is achieved. An IFM system is then experimentally demonstrated based on the few-mode fiber-based microwave photonics filters. The system uses two different wavelengths, which are modulated by an intensity modulator and a phase modulator, respectively. Two MPFs with different lowpass and bandpass frequency responses are obtained, and an ACF is established with the ratio of the two frequency response curves. The target microwave frequency is retrieved by calculating the ratio of two detected microwave powers and comparing it with the established ACF curve. A measurement range of 0.5 GHz to 17.5 GHz and a measurement accuracy of ±0.2 GHz in most frequency points have been achieved. With FMF, the proposed measurement system has the advantage of integration and simplicity, since there is no need to utilize multiple fibers or inscribe gratings in the fiber to introduce additional time delay. The fabrication of FMF-based photonics link has high repeatability, and the used FMF is cost-effective. Therefore, it is very promising for practical applications.

Funding

National Key Research and Development Program of China (2018YFB1801701); National Natural Science Foundation of China (U1701661).

Disclosures

The authors declare that there are no conflicts of interest.

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