

Instantaneous frequency measurement with adjustable measurement range and resolution based on polarisation modulator

Hualin Zhang and Shilong Pan

An instantaneous frequency measurement scheme incorporating a polarisation-modulator-(PoIM)-based link is proposed and demonstrated. With the adjustable dispersion-induced microwave power penalties in the PoIM-based link, the measurement range and resolution can be easily tuned. Therefore, optimised resolution for a specific measurement range can be achieved. An experiment has been performed and a frequency measurement range of 3.3–18.7 GHz with a measurement resolution of ± 0.15 GHz was achieved.

Introduction: Quick and accurate measurement of the frequency of intercepted microwave signals is a basic function of electronic warfare (EW) systems [1]. Compared with the traditional microwave frequency measurement in the electronic domain, photonic-assisted approaches show distinctive advantages in terms of instantaneous measurement, large measurement range, small size, low power assumption, and immunity to electromagnetic interference [2–6]. One of the key challenges for the photonic instantaneous frequency measurement is that there is a trade-off between the measurement range and the measurement accuracy. Higher measurement resolution results in a smaller measurement range. One possible solution is to construct a system with an adjustable measurement range, so that the measurement resolution can be optimised for specialised applications. Previously, Zou and Yao proposed a scheme to implement a tunable measurement range using a Mach-Zehnder modulator (MZM) and two/three lasers with a wavelength tuning range as large as 130 nm [3], which is too expensive to be used in a practical system. Li *et al.* demonstrated a reconfigurable instantaneous frequency measurement (IFM) system based on a dual-parallel MZM and an MZM [4]. The key limitations associated with the method are the large insertion loss, complex bias setting and the bias drifting problem of the dual-parallel MZM. Although the frequency measurement range of the approaches in [5, 6] can be adjusted by tuning the wavelength of the laser or the dispersion of the dispersive elements, recalibration is needed to ensure measurement accuracy, making the system unable to perform instantaneous measurement.

In this Letter, a novel microwave frequency measurement scheme based on a polarisation modulator (PoIM) and a polarisation beam splitter (PBS) is proposed and demonstrated. By simply adjusting polarisation controllers (PC) placed between the PoIM and PBS, the measurement range and resolution can be continuously adjusted.

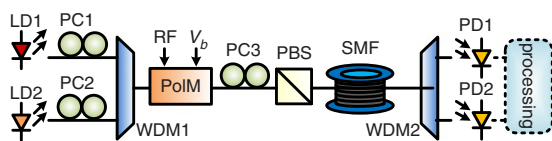


Fig. 1 Schematic of proposed microwave frequency measurement system
LD: laser diode; PC: polarisation controller; SMF: singlemode fibre; WDM: wavelength division multiplexer; PoIM: polarisation modulator; PBS: polarisation beam splitter; PD: photodetector

Principle: The schematic of the proposed system for instantaneous microwave frequency measurement is shown in Fig. 1, which includes two laser diodes (LDs), three PCs, two wavelength division multiplexers (WDMs), a PoIM, a PBS, a section of singlemode fibre (SMF), and two photodetectors (PDs). A microwave signal with its frequency to be measured is applied to the PoIM via its RF port, to modulate the two linearly polarised CW lightwaves from the LDs. The polarisation directions of the lightwaves are aligned to have an angle of 45° to the same principal axis by PC1 and PC2. The PoIM is a special phase modulator supporting both TE and TM modes but with opposite phase modulation indices [7]. The output signal from the PoIM is sent to the PBS via PC3. The SMF, serving as a dispersive element, is used to introduce dispersion-induced microwave power penalties to the two wavelengths. The two wavelengths are then separated by the WDM and converted back to electrical signals in the two PDs. The microwave powers are

measured and used to estimate the microwave frequency in a post-processing stage.

Mathematically, when a lightwave is sent to a PoIM-based link, the AC term of the output current from the PD is written as [8]

$$i_{PD} \propto 2J_0 J_1 \left[\sin 2\alpha \cos\left(\frac{1}{2} D_\omega \omega_m^2\right) \sin \phi_0 + \cos 2\alpha \sin\left(\frac{1}{2} D_\omega \omega_m^2\right) \cos[\omega_m(t - \tau_0)] \right] \quad (1)$$

where ω_m is the angular frequency of the modulating signal, J_n is the n th-order Bessel function of the first kind, $D_\omega = -D\lambda^2/(2\pi c)$, D , λ and c represent the total dispersion of the dispersive element, the wavelength of the optical carrier and the speed of light in vacuum, respectively, ϕ_0 is the phase difference between the signals along the two principal polarisation axes which can be changed by adjusting the DC bias of the PoIM, α is the angle between the principal axis of the PBS and one principal axis of the PoIM, and τ_0 is the time delay in the optical devices.

Tuning the DC bias of the PoIM to let $\phi_0 = \pi/2$, (1) can be simplified to

$$i_{PD} \propto 2J_0 J_1 \sin(2\alpha + \frac{1}{2} D_\omega \omega_m^2) \cos[\omega_m(t - \tau_0)] \quad (2)$$

When two wavelengths λ_1 and λ_2 are transmitted through the PoIM-based link, by comparing the microwave powers from the two PDs at the post-processing stage, we can obtain the amplitude comparison function (ACF):

$$ACF = \frac{P_{PD1}}{P_{PD2}} = \eta \frac{\sin^2[\pi D_1 \lambda_1^2 f_m^2 / c - 2\alpha]}{\sin^2[\pi D_2 \lambda_2^2 f_m^2 / c - 2\alpha]} \quad (3)$$

where η represents the difference of the insertion losses in the two channels, $f_m = \omega_m/2\pi$, D_1 and D_2 are the total dispersions at the two wavelengths, respectively. By adjusting the optical power of the LDs, we can achieve $\eta = 1$. From (3), the ACF is monotonically increasing or decreasing from DC to a frequency f_{max} at which the ACF reaches its first extreme value, and has no relationship with the power of the input microwave signal, so f_m can be estimated without ambiguity in this frequency range.

The highest measurable frequency f_{max} is highly dependent on α and is given by

$$f_{max} = \begin{cases} \sqrt{c/(D\lambda^2)_{max}} & \alpha=0 \\ \sqrt{2\alpha c/\pi(D\lambda^2)_{max}} & 0 < \alpha \leq \pi/2 \end{cases} \quad (4)$$

where $(D\lambda^2)_{max}$ is equal to either $D_1\lambda_1^2$ or $D_2\lambda_2^2$, whichever is greater. Since α can be easily adjusted by PC3, the measurement range as well as the resolution can also be tuned by PC3.

Fig. 2a shows the simulation results of the power-fading functions and the corresponding ACF when $\alpha = 0$. In the simulation, the laser wavelengths are 1527.566 and 1565.056 nm, the dispersive element is a 20 km SMF, and the total dispersions at the two wavelengths are 307.2 and 349.2 ps/nm, respectively. As shown in Fig. 2a, the variation of the ACF is very small in the range 0 to ~ 15 GHz. Therefore, the measurement resolution will be very low. Only when the measured microwave frequencies are near the notch point, will the measurement resolution be improved. By simply adjusting PC3 to change α , the measurement range can be easily tuned. Fig. 2b depicts the ACF curves when α is equal to $0.05n\pi$ ($n=1\dots 10$). As can be seen, the notch point of the ACF curve shifts from 5.92 to 18.73 GHz. As a result, by adjusting α , we can select the most suitable ACF curve to measure the frequency in a specific frequency band. This enables us to estimate the microwave frequency with a relatively high resolution over a wide frequency range.

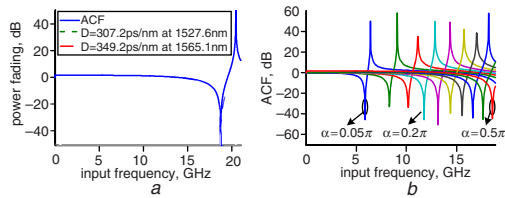


Fig. 2 Calculated results

a Power fading functions and resulting ACF when $\alpha = 0$
 b Calculated ACF for different α

Measurement results and discussion: A proof-of-concept experiment was performed. A tunable laser source (Agilent N7714A), a PoIM (Versawave Inc.) with a bandwidth of 40 GHz, a spool of 20 km SMF and a 50 GHz PD were used to construct the PoIM-based link. The transmission response of the link was measured by a vector network analyser (VNA, Agilent N5230A). The output power of the electrical signal from the VNA was fixed at 0 dBm. The ACF is achieved by comparing the transmission responses of the link at 1527.566 and 1565.056 nm.

In the experiment, we adjusted PC3 to increase α from 0.05π to 0.5π , by steps of 0.05π . Fig. 3a shows three typical ACF curves. The calculated results and the measured ones match very well. Fig. 3b shows the measured frequencies against input frequency. To obtain the optimised resolution, the frequencies in a specific band are measured by a specific α . The measured results agree with theoretical values well. Fig. 4 shows the measurement error from 3.3 to 18.7 GHz using the α setting listed in Table 1. In the entire measurement range except 16.05 GHz, the measurement error is within ± 0.15 GHz. We should note that poor resolution would result if α is not optimally set. For example, if we try to measure the frequency in the range 9.1–12.4 GHz, and α is adjusted to be 0.35π , the resolution is dramatically degraded to ± 0.25 GHz, indicating the proposed scheme can increase the measurement resolution by simply adjusting the angle between the principal axis of the PBS and one principal axis of the PoIM.

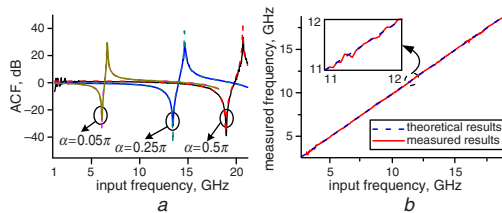


Fig. 3 Measured results

a ACF curves at different α
 b Measured microwave frequencies when input microwave frequency tuned from 3.3 to 18.7 GHz
 Inset: Zoom-in view of measured microwave frequencies

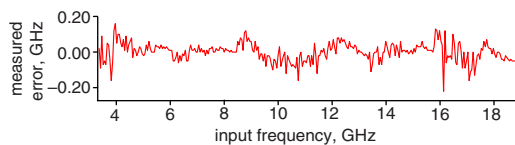


Fig. 4 Distribution of measurement errors

Table 1: Measurement range and resolution for different α

α	Measurement range (GHz)	Resolution (GHz)
0.05π	3.3–5.9	± 0.15
0.1π	4.5–8.25	± 0.15
0.25π	7.9–13.2	± 0.15
0.35π	12.4–15.6	± 0.15
0.5π	15.6–18.7	± 0.15

Conclusion: A simple, flexible microwave frequency measurement scheme based on a PoIM is proposed and demonstrated. By simply adjusting a polarisation controller in the scheme, an optimised measurement resolution of ± 0.15 GHz was achieved in a frequency measurement range of 3.3–18.7 GHz.

Acknowledgments: This work was supported in part by the National Natural Science Foundation of China (61107063), the National Basic Research Program of China (2012CB315705), the Jiangsu Provincial Funds for Distinguished Young Scientists (BK2012031), National Aerospace Science Foundation of China (2012ZD52052), the Fundamental Research Funds for the Central Universities (NE2012002), and a Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions.

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9 October 2012

doi: 10.1049/el.2012.3552

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