Novel photonic approach to microwave frequency measurement using tunable group delay line

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A photonic approach for measuring microwave frequency over a wide bandwidth is proposed. An optic group delay line composed of several magneto-optical switches and a 1.6-km single-mode fiber is used as a tunable dispersive medium in the measurement setup. A minimum frequency accuracy of 80 MHz in the range of 1–20 GHz is achieved experimentally.

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The photonic technique has been considered an alternative approach to processing radar signals in electronic warfare[1]. The optical processing of microwave signals offers more advantages over conventional electronic systems, such as reduction of device size and weight, increase in signal bandwidths, low loss, and immunity to electromagnetic interference. One of the basic applications of this technique is microwave frequency measurement. Previously, a tunable Fabry-Perot interferometer was used for microwave frequency measurement[2]. In the last few years, several other experimental approaches based on amplitude comparison function were developed for measuring the frequency of a microwave signal[3−7]. Some of these methods suffer from the measurement range restriction[5,6]. Microwave frequency measurement was also attained by analyzing the photodetector direct current (DC) voltage[8] and photonic Hilbert transform[9]. The measurement accuracy of these methods can be achieved from several megahertz to tens of megahertz over a wide frequency range. Recently, a measured error within ±400 kHz over a narrow band has been realized[10]. However, the measurement systems often use a tunable laser source and tens of kilometers of single-mode fibers (SMF) or photonic filters, making these systems costly, bulky, complex, and unsuitable for some applications.

A novel photonic approach for measuring microwave frequency has been proposed recently[11]. A phase difference of the two optical carriers with the same microwave signal is induced by chromatic dispersion. By tuning one of the optical wavelengths, the interference microwave power of the two signals is tuned periodically. The microwave frequency can be extracted by measuring the interference power. Although this method can provide good accuracy and a broadband measurement range, it still has interior drawbacks. The fiber dispersion coefficient varies with the different optical wavelengths, which can cause a calculation error. The measurement range is restricted by the fading effect[12] and leads to some blind measurement region. In this letter, we propose a new method to tune dispersion using two fixed wavelengths and shorter SMF, which can effectively avoid these limitations. A tunable group delay line composed of optical switches and SMF is used as a tunable dispersion medium (TDM) to generate the incremental chromatic dispersion in frequency measurements for the first time. The measurement frequency range of 1–20 GHz can be achieved with an accuracy of −80–10 MHz. This simple system with two distributed feedback lasers and a 1.6-km SMF shows portable and inexpensive characteristics for microwave frequency measurement.

The schematic diagram of the proposed approach is shown in Fig. 1. In this approach, two optical carriers from two laser diodes (LDs) are combined in an optical coupler through two polarization controllers, respectively. A microwave signal is modulated onto the two optical carriers with a Mach-Zehnder modulator (MZM) biased at the linear point. The two optical carriers from the MZM are sent to a TDM. The TDM is similar to a binary fiber optic delay line[13] that consists of two 1×2 and five 2×2 optical switches linked in tandem. A total of 64 (0–63Δl) different SMF lengths can be provided by a 6-bit delay line with a step of Δl. Different dispersions are introduced to two wavelengths by the TDM, leading to a microwave phase difference at the photodetector (PD). Due to the interference effect, the microwave power output from the PD shows a periodic characteristic by tuning the TDM step by step. Thus, the frequency can be calculated according to the period.

The two optical carriers arrive at the PD at different times due to the chromatic dispersion generated by the SMF. Hence, the microwave signals carried by the

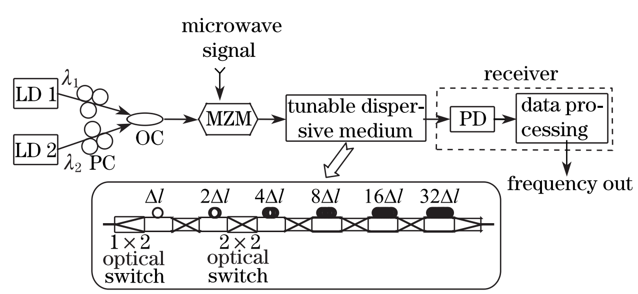

Fig. 1. Schematic of the proposed approach for microwave frequency measurement (PC: polarization controller; OC: optical coupler).

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two optical wavelengths obtain a phase difference. The amplitudes of the two microwave signals before the receiver are given by[14]

$$E_1 \propto E_{10} \cos\left(\frac{\pi D L \lambda_1^2 f^2}{c}\right) \cdot \cos\left(\omega_c t + \varphi_1\right), \quad (1a)$$

$$E_2 \propto E_{20} \cos\left(\frac{\pi D L \lambda_2^2 f^2}{c}\right) \cdot \cos\left(\omega_c t + \varphi_2\right), \quad (1b)$$

where f is the microwave frequency, $\omega_c = 2\pi f$, c is the light velocity in vacuum, D is the material dispersion coefficient of the SMF, and L is the length of the SMF. φ_1 and φ_2 are the phases of the two microwave signals through the TDM.

To realize a pure interference effect at the receiver, E_1 and E_2 should have equal amplitudes by assuming the two wavelengths λ_1 and λ_2 with the same optical power. Therefore, we have $E_{10} = E_{20} = E_0$. The interferential microwave power P_{MW} at the output of the PD can be expressed as

$$\begin{aligned} P_{MW} &\propto |E_1 + E_2|^2 \\ &\propto E_0^2 \cos^2\left(\frac{\pi D L \lambda_1^2 f^2}{c}\right) + E_0^2 \cos^2\left(\frac{\pi D L \lambda_2^2 f^2}{c}\right) \\ &+ 2E_0^2 \cos\left(\frac{\pi D L \lambda_1^2 f^2}{c}\right) \cos\left(\frac{\pi D L \lambda_2^2 f^2}{c}\right) \cdot \cos(\Delta\varphi), \quad (2) \end{aligned}$$

where $\Delta\varphi = |\varphi_1 - \varphi_2|$ is the phase difference between the two microwave signals. In Eq. (2), the P_{MW} can be changed periodically by tuning the length of the SMF in TDM. The fiber length is set to be switched from L_1 to L_2. Thus, the phase difference $\Delta\varphi$ is expressed by

$$\Delta\varphi = 2\pi f \cdot \Delta\lambda \cdot D \cdot |L_1 - L_2|, \quad (3)$$

where $\Delta\lambda = |\lambda_1 - \lambda_2|$ is the wavelength difference of the two LDs. We assume that the optical loss of the TDM is constant as the fiber length changes. The fading effect can be neglected because the total dispersion is small, and the frequency to be measured is low[12]. In Fig. 2, the P_{MW} varies cosinusoidally, with the SMF lengthening continuously. The microwave frequency can be calculated from Eq. (3) as

$$f = \frac{1}{2 \cdot \Delta D \cdot \Delta L}, \quad (4)$$

where $\Delta L = |L_1 - L_2|$ is the half-period of the curve of the measured power versus fiber length. $\Delta D = \Delta\lambda \cdot D$ is the dispersion value of the SMF within $\Delta\lambda$, the unit of which is ps/km. As ΔD is a constant for a given SMF within fixed λ_1 and λ_2, the calculated error caused by the dispersion slope in Ref. [11] can be improved.

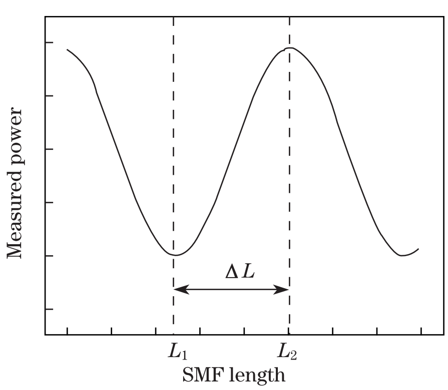

Fig. 2. Schematic curve of the measured power versus SMF length.

To verify the concept of measuring the microwave frequency, experiments are carried out using the setup in Fig. 1. The wavelengths of the two LDs are selected as 1,545.67 and 1,555.63 nm, as measured by a wavelength meter (Exfo WA-7600, Canada). The optical powers of the two wavelengths are both set to −7 dBm at the output of the MZM (Covega Mach-LN^{TM} 058, USA). Two 1×2 and five 2×2 magneto-optical switches controlled through a Lab VIEW interface are used in a 6-bit TDM. All optical switches have a switching speed between 10 and 30 μs. The 6 different lengths of the SMF are set to 25, 50, 100, 200, 400, and 800 m, respectively. The total fiber length of the TDM can then be changed from 0 to 1,575 m by a step of 25 m. The chromatic dispersion value (ΔD) of the SMF between the wavelength 1,545.67 and 1,555.63 nm is 162.09 ps/km, as measured by the modulation phased-shift (MPS) method with an RF network analyzer (Agilent E7051C, USA)[15]. The RF power from the PD (u2t 2120R, German) is measured by a microwave power meter (Agilent E4440A, USA) when the microwave frequency is tuned from 1 to 20 GHz.

The theory mentioned before is based on a constant optical loss of the TDM. Gain equalization should be conducted on the received RF power because the insertion loss of the TDM is not fixed. This inequality is caused by the difference between the cross and bar states of the optical switches and the SMF connections. In the experiment, the optical insertion losses of the TDM are 6–7.5 dB, leading to a maximum RF gain undulation of 3 dB. By comparing the measured microwave power of the two interference carrier waves with that of one carrier wave, the loss non-uniformity caused by TDM can be eliminated, and the fading effect can be reduced. As the optical switches have fast response property (<30 μs), this process occurs in a very short time, and the influence of the measuring speed is small.

Figure 3 shows the equalized measurement power and the fitted curve of a 10 GHz microwave signal. ΔL is confirmed by a nonlinear regression using the sine function. Based on Eq. (4), the ΔL is fitted as 309.96 m, and the calculated frequency is 9.952 GHz with an error of 48 MHz.

The relationship between the measured frequency and the input frequency of the microwave signals is presented in Fig. 4. Figure 5 shows the difference by which the measurement error can be achieved. The proposed

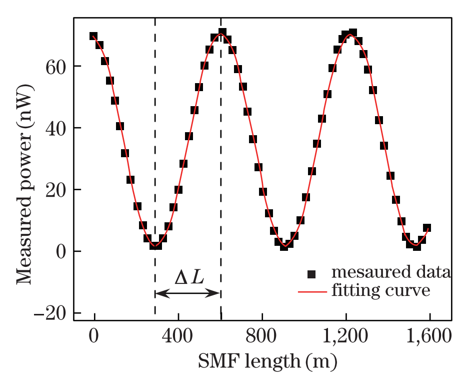

Fig. 3. Measured power versus SMF length.

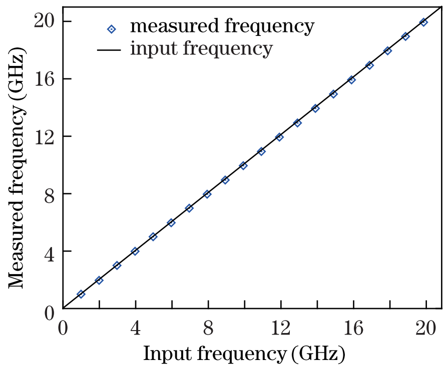

Fig. 4. Measured frequency as a function of the input frequency.

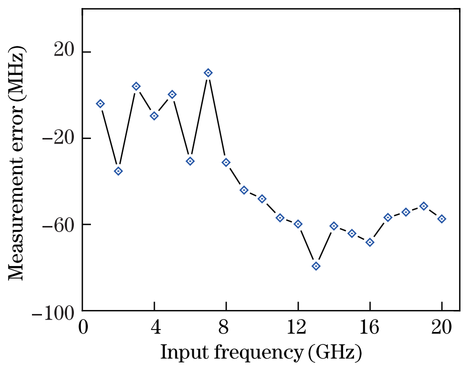

Fig. 5. Measurement errors in the 1–20 GHz range.

approach yields a measurement error of −80–10 MHz for a wide range of 1–20 GHz. Good accuracy is achieved without changing the optical wavelengths or total SMF length. To obtain higher interference power, the RF power is set to 10 dBm in the experiments. By increasing the optical power or reducing the link losses, the minimum measurable power of this method is expected to improve to under −10 dBm.

According to Eq. (2), when the fiber length increases, the fading effect can only cause the peak value to decrease and does not have any effect on the spectrum period. Thus, the frequency error caused by the fading effect is negligible. The measurement error is mainly caused by the MZM bias drift and LD power fluctuations, which induce a 0.2-dB ripple in the measured microwave power. This may lead the error to become several tens of megahertz. To reduce these effects, the LDs and the MZM should be stabilized to the operating current and temperature. The chromatic dispersion of the SMF and the wavelength drift of the LDs also contribute to the measurement error. The MPS method induces a 1–2 ps/km dispersion measurement error, and the wavelengths of the LDs have a 0.001-nm ripple. In the 10-GHz measurement, this wavelength drift yields a 1-MHz error with 10-nm wavelength spacing. Moreover, to improve the measurement accuracy, the measurement of the SMF length and microwave power should be more accurate.

The measurement error generated by data fitting can be improved by augmenting the data amount and density using several more optical switches and shorter Δl. For example, a 9-bit TDM, Δl=5 m (the total SMF length can reach 2 560 m) is a better scheme. Using a high dispersion fiber[16] and a larger $\Delta\lambda$, the total length of the fiber can decrease to tens of meters. Moreover, the larger wavelength spacing of the two LDs can decrease the influence of the wavelength drift. The system bulk can be reduced using the MEMS optical switch[17], and the measurement range can be further extended by increasing the bandwidths of the modulator and PD[18].

In conclusion, we have proposed and demonstrated a photonic approach for microwave frequency measurement. The measurement setup uses a 6-bit tunable group delay line composed of 7 magneto-optical switches and a 1.6-km SMF as a TDM. The broad frequency measurement range of 1–20 GHz can be achieved with an accuracy of 80 MHz. The method's broad range, good accuracy, and simple setup make it a promising alternative in microwave frequency measurement.

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