Microwave frequency measurement with improved measurement range and resolution

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An approach is proposed and demonstrated to improve the measurement range and resolution of a microwave frequency measurement system. Two optical wavelengths are modulated by a microwave signal in a Mach-Zehnder modulator (MZM). The optical output from the MZM is sent to a dispersive element to introduce different chromatic dispersions, leading to different microwave power penalties. A fixed relationship between the microwave power ratio and the microwave frequency is established. The microwave frequency is estimated by measuring the microwave powers. A new measurement range is defined with an improved measurement range and resolution. Analysis is performed and confirmed by an experiment.

Introduction: Recently, several techniques have been proposed for microwave frequency measurement in the optical domain [1–8]. The key motivation for using a photonic approach to perform microwave frequency measurement is the wideband and near real-time frequency measurement offered by photonics, which may not be possible using an electronic approach. In addition, photonic approaches have other advantages such as small size, low loss, and immunity to electromagnetic interference. In general, the measurement techniques in the optical domain can be classified into two categories. In the first category, a microwave frequency is measured using a wideband optical channeliser, such as electro-optic waveguide delay lines [1], a high-resolution diffraction grating [2], an array of phase-shifted gratings [3], an integrated Bragg grating with a Fresnel lens [4], and an optical etalon incorporated with a wavelength splitter [5]. In the second category, a microwave frequency is measured by monitoring the optical [6] or microwave powers [7, 8]. In [6] the frequency was estimated by monitoring and comparing the optical powers at the outputs of two optical channels with complementary frequency-dependent optical losses, based on a fixed relationship between the optical power ratio and the microwave frequency. In [7, 8] the microwave frequency was estimated by comparing the microwave powers for two optical channels having different frequency-dependent power penalties. Thanks to a fixed relationship between the microwave power ratio and the microwave frequency, the microwave frequency is estimated if the two microwave powers are measured.

A major limitation of the approaches in [6–8] is that the measurement range and resolution are limited owing to the use of a region where the slope of the power ratio against the microwave frequency is small. The system noise would significantly impact on the measurement accuracy. To improve the measurement resolution without complicating the system, we define a new frequency measurement range which exhibits fast variation in the power ratio against the microwave frequency, leading to an improved measurement range and resolution.

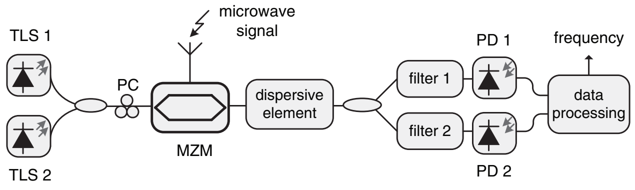

Fig. 1 *Schematic diagram of proposed approach*

TLS: tunable laser source; PC: polarisation controller; MZM: Mach-Zehnder modulator; PD: photodetector

Principle: The system for microwave frequency measurement is shown in Fig. 1. Two tunable laser sources (TLSs) are modulated by an unknown microwave signal. The two intensity-modulated wavelengths after passing a dispersive element are then separated by two optical filters, with the corresponding microwave powers being measured. The microwave powers at the outputs of the two photodetectors are not a constant, but a function of the microwave frequency, since the chromatic dispersion induced power fading is a function of the microwave frequency. Assume that the dispersions at the two wavelengths λ_1 and λ_2 are, respectively, χ_1 and χ_2, the two microwave powers are $P_1 = A_1[\cos(\pi\chi_1\lambda_1^2 f^2/c+\alpha)]^2$ and $P_2 = A_2[\cos(\pi\chi_2\lambda_2^2 f^2/c+\alpha)]^2$. If the link losses, A_1 and A_2, at the two channels are controlled identically, then we have the power ratio given by

$$\gamma = \frac{P_1}{P_2} = \frac{[\cos(\pi\chi_1\lambda_1^2 f^2/c+\alpha)]^2}{[\cos(\pi\chi_2\lambda_2^2 f^2/c+\alpha)]^2} \tag{1}$$

where c is the light velocity in vacuum, α is the chirp parameter of the Mach-Zehnder modulator (MZM). Equation (1) provides a fixed relationship between the microwave frequency and the microwave powers. The microwave frequency can be estimated by measuring the two microwave powers. From (1) we can also see that the microwave frequency is independent of the received microwave power.

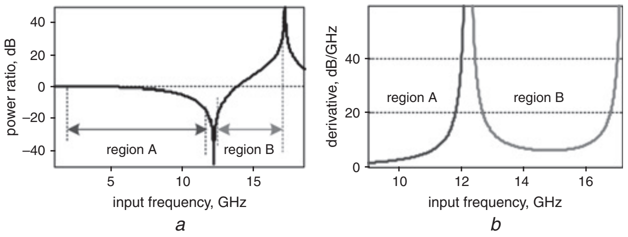

Fig. 2 *Simulation results*

a Calculated power ratio against input microwave frequency
b Absolute value of first-order derivative of power ratio

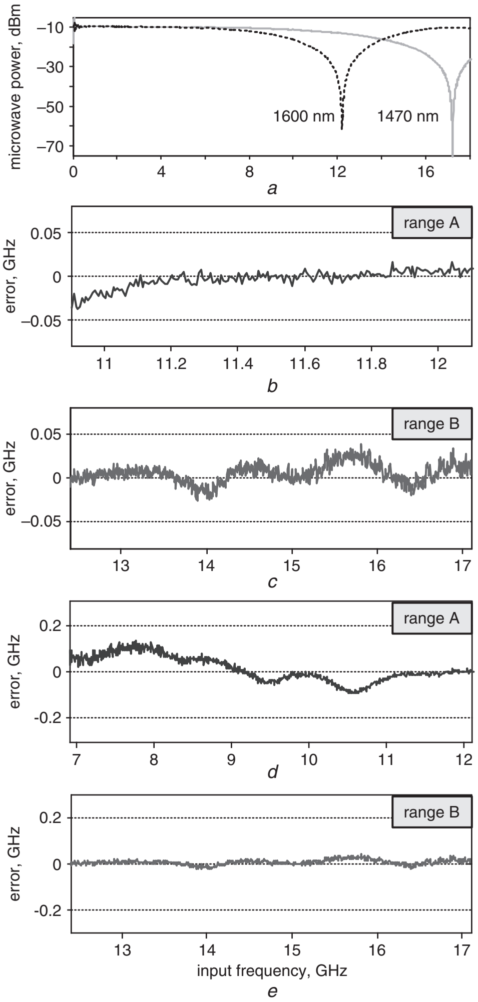

Fig. 3 *Experimental results*

a Measured microwave powers against microwave frequency
b and *c* Measurement errors in regions A and B for a given measurement error, region B offers a larger measurement range than region B.
d and *e* Measurement errors in regions A and B for an identical measurement range, region B provides much better noise performance

Fig. 2*a* shows the power ratio against the microwave frequency, which is obtained assuming the dispersive fibre is a 20 km standard singlemode fibre (SSMF), the MZM is chirp-free, and the two wavelengths are set at 1470 and 1600 nm. As can be seen, two regions may be used to estimate the microwave frequency, region A and region B. In region A, the variation of the power ratio against the microwave frequency is slow. For a range with a slow variation, the measurement resolution would be poor, especially when the system is with noise [7, 8]. If we compare region A with region B in Fig. 2*a*, we will find that region B has much faster variation. Fig. 2*b* shows the absolute values of the first-order derivatives for the two regions. The variation in the entire region B is much faster than that in region A. Hence, the use of region B would provide a better measurement resolution. In addition, for a given variation rate, region B has a larger frequency range than region A. Therefore, the use of region B would also increase the measurement range. For instance, the measurement range in region B is 12.3–17.1 GHz with a minimum absolute derivative of 6.14 dB/GHz; while the measurement range in region A is 9.9–12.2 GHz with a minimum absolute derivative of 2.5 dB/GHz. Therefore, the use of region B improves both the measurement range and resolution.

Experiment and discussion: An experiment is performed to evaluate the improvement of the frequency measurement system. In the experiment, the dispersive element is a 20 km SSMF, the two wavelengths are set at 1470 and 1600 nm, and the loss difference is compensated for by adjusting the powers of the TLSs although the link losses at the two wavelengths are slightly different. The microwave power distributions with dispersion-induced power penalties are measured by a vector network analyser (VNA, Agilent E8364A). The microwave frequency is then estimated by calculating the power ratio with the measurement errors shown in Fig. 3. For an identical measurement error of ±0.03 GHz, the measurement ranges for region A and region B are, respectively, 10.9–12.1 GHz (1.2 GHz) and 12.3–17.1 GHz (4.8 GHz). A much larger measurement range of 4.8 GHz is obtained for region B, compared to 1.2 GHz for region A, as shown in Figs. 3*b* and 3*c*. On the other hand, for an identical measurement range of 4.8 GHz, region B provides much better noise performance than region A, as shown in Figs. 3*d* and 3*e*.

The improvement can be explained by considering the operation robustness to the system noise. For a noise-free system, one can get accurate results even though the absolute derivative of the power ratio is small. However, in practice noise would affect the measurement accuracy inevitably. As a result, a higher absolute derivative is required to mitigate the destructive impact of the system noise. Assume that the noise field follows a Gaussian distribution in the case of the central limit theorem [9]. Taking the noise into account, a smaller measurement error could be achieved in region B with a given signal-to-noise ratio (SNR). For example, for an SNR of 10.5 dB, the simulated measurement errors for an identical measurement range of 4.7 GHz are ±0.2 and ±0.03 GHz for region A and region B, respectively.

Furthermore, according to (1), a tunable measurement range can be achieved by adjusting the dispersion coefficient of the dispersive element or the chirp parameter of the MZM. For practical applications, region B should be designed to have a measurement range to cover the entire frequency band of interest. To avoid measurement ambiguity caused by the existence of region A, we may use a highpass filter with a stopband covering the entire frequency range of region A, to ensure only a microwave frequency falling in the range of region A will be estimated.

Conclusion: A new region is defined for the measurement of microwave frequency with improved measurement range and resolution. The key to the improvement is due to the use of the region that has a much faster variation in the power ratio against microwave frequency. The improvement in measurement range and resolution has been analysed and experimentally verified.

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