Instantaneous microwave frequency measurement based on hybrid microwave photonic filter*

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(Received 4 June 2014)

A novel photonic technique for instantaneous microwave frequency measurement based on hybrid microwave photonic filter (HMPF) is proposed and experimentally demonstrated. The HMPF is composed of an all-pass filter and a band-pass filter with negative coefficients. By properly controlling the power relationship between the all-pass filter and the band-pass filter, the HMPF can realize a monotonic frequency response, and then a unique relationship between the output power and the input frequency is established. A high measurement resolution can be achieved for a given frequency range.

Document code: A **Article ID:** 1673-1905(2014)05-0374-4

DOI 10.1007/s11801-014-4100-0

Up to now, many photonic approaches have been proposed to implement microwave frequency measurement, in which the frequency-to-time mapping technique is usually complex and expensive[1], and the frequency-to-space mapping technique is usually bulky and costly[2], while the frequency-to-power mapping technique for instantaneous frequency measurement (IFM) of microwave signal has attracted considerable attention[3-11]. The IFM system has several limitations, such as wavelength drift[3-5], relative power fluctuations[6-9] and parameters mismatch between the multiple modulators[10,11]. Recently, a technique has been proposed to implement microwave frequency measurement by using a microwave photonic filter[12,13]. The technique can improve the performance of IFM system in which only one laser source, one modulator and one photodetector (PD) are needed. In Ref.[12], an IFM system is demonstrated using an electrical feedback infinite impulse response (IIR) filter cascaded with a two-tap finite impulse response (FIR) filter to obtain a sharply varying monotonic microwave frequency response. However, the spectral width of the laser source severely limits the system stability, and an electrical feedback loop with a broadband radio frequency (RF) amplifier is needed. In Ref.[13], a scheme for IFM is presented based on an amplified recirculating delay line (RDL) loop and a broadband incoherent light source, while the limitation of the scheme is that the light source is not a communication-typed laser source.

In this paper, we propose a novel technique for IFM using a hybrid microwave photonic filter (HMPF). The HMPF is the combination of an all-pass filter and a band-pass filter with negative coefficients, and the band-pass filter is implemented using an RDL loop with a semiconductor optical amplifier (SOA) and a tunable optical band-pass filter (TOBF). By properly controlling the power relationship between the all-pass filter and the band-pass filter, the HMPF realizes a sharply varying monotonic microwave frequency response without an electrical feedback loop or a broadband incoherent light source. The proposed IFM system only requires one laser source, one modulator and one PD, which greatly lowers the complexity and reduces the cost of the measurement system. Thanks to the theoretical infinite power variation of the response, a high measurement resolution can be achieved.

The schematic diagram of the proposed instantaneous microwave frequency measurement system is shown in Fig.1. The light from a laser diode (LD) is sent to a Mach-Zehnder modulator (MZM) which is driven via one RF port by an unknown continuous-wave (CW) microwave signal for which the frequency is to be measured. At the output of the MZM, the modulated signal light is split into two paths. In the upper path, the modulated signal passes through an attenuator (ATT) to operate as an all-pass filter. In the lower path, the modulated signal enters an amplified RDL loop, consisting of an

* This work has been supported by the National Natural Science Foundation of China (Nos.61302026, 61275067 and 61007064), the Jiangsu Natural Science Foundation (Nos.BK2012432 and BK2012830), the PhD Programs Foundation of the Ministry of Education of China (No.20123223120005), the Natural Science Foundation of the Jiangsu Higher Education Institutions (No.13KJB510025), and the Key Project of the Natural Science Foundation Project of Chongqing (No.cstc2013jjB20004).

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SOA, a TOBF and an optical coupler (OC: OC1). The pump signal is copied onto the amplified spontaneous emission (ASE) due to the cross gain modulation (XGM) of the SOA. The inversely modulated signal can be extracted from the ASE by the TOBF detuned from the pump wavelength, and it has an inverse phase compared with the pump signal and circulates in the RDL loop for realizing a band-pass filter with negative coefficients. The lengths of the two paths are controlled to be equal to each other to enable the upper modulated signal and the first tap of the band-pass filter to arrive at the PD simultaneously. At the OC4, the upper and the lower modulated signals are combined, and the interference between them can also be avoided due to wavelength conversion in the lower path employing the XGM of the ASE in the SOA. After photodetection, the band-pass filter with negative coefficients combined with the all-pass filter realizes a monotonic frequency response.

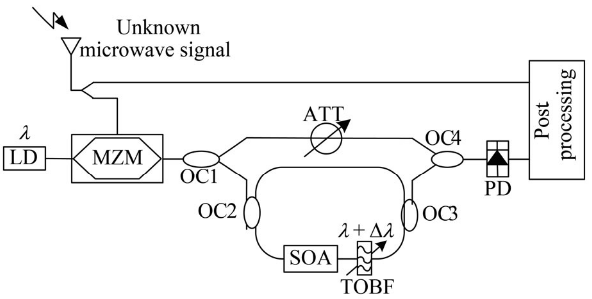

Fig.1 Schematic diagram of the proposed instantaneous microwave frequency measurement system

The transfer function of the band-pass filter with negative coefficients shown in the lower path of Fig.1 is given by

$$H_{\mathrm{b}}(f_{\mathrm{m}}) = -\frac{(1-\kappa_1)(1-\kappa_2)(1-\kappa_3)(1-\kappa_4)g_{\mathrm{c}}}{(1-\kappa_2\kappa_3 g_{\mathrm{c}} \mathrm{e}^{-\mathrm{j}2\pi f_{\mathrm{m}}T})}, \qquad (1)$$

where κ_1, κ_2, κ_3 and κ_4 are the coupling coefficients of the OC1, OC2, OC3 and OC4, respectively, g_{c} is the effective gain of converted signal, f_{m} is the modulating frequency of the microwave signal, and T is the time delay of the RDL loop.

After the combination of the all-pass filter and the band-pass filter, the overall transfer function of the HMPF shown in Fig.1 can be written as

$$H_{\mathrm{o}}(f_{\mathrm{m}}) = \underbrace{a\kappa_1\kappa_4}_{H_{\mathrm{a}}} \underbrace{- \frac{(1-\kappa_1)(1-\kappa_2)(1-\kappa_3)(1-\kappa_4)g_{\mathrm{c}}}{(1-\kappa_2\kappa_3 g_{\mathrm{c}} \mathrm{e}^{-\mathrm{j}2\pi f_{\mathrm{m}}T})}}_{H_{\mathrm{b}}}, \qquad (2)$$

where a is the optical loss coefficient controlled by the ATT, and H_{a} and H_{b} represent the all-pass filter function and the band-pass filter function, respectively.

Control the power relationship between the all-pass filter and the band-pass filter, and make it satisfy the following expression of

$$a\kappa_1\kappa_4 = \frac{(1-\kappa_1)(1-\kappa_2)(1-\kappa_3)(1-\kappa_4)g_{\mathrm{c}}}{(1+\kappa_2\kappa_3 g_{\mathrm{c}})}. \qquad (3)$$

A monotonic frequency response varying from positive infinity to negative infinity can be realized. In the design, κ_1, κ_2, κ_3 and κ_4 are 0.5, 0.5, 0.9 and 0.5, respectively, and g_{c} is 2.18. The theoretical response is simulated and shown in Fig.2.

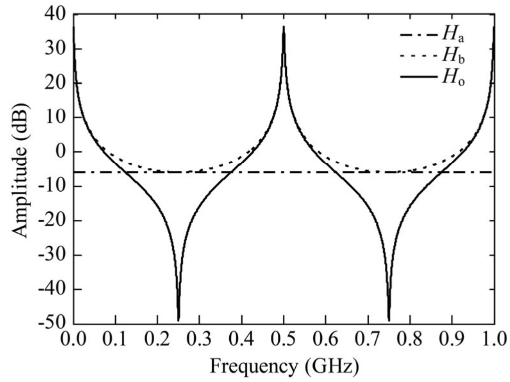

Fig.2 Calculated frequency response of the HMPF

Assuming that the input signal power is normalized, and neglecting the direct current (DC) component and the small second harmonic frequency component, the output power of microwave signal can be expressed as[11]

$$P_{\mathrm{out}} \propto \Re^2 J_0^2(m) J_1^2(m) \left| H(f_{\mathrm{m}}) \right|^2, \qquad (4)$$

where $\Re$ is the responsivity of the PD, m is the modulation index which is related to the input microwave power, and $J_i(\cdot)$ with i=0, 1 are the first kind Bessel functions. Finally, a small portion of the input microwave signal is tapped out and used to perform the corresponding amplitude comparison in the post-processing unit. Based on Eq.(4), a calibrated look-up table can be established, and thus the frequency of the input microwave signal can be extracted.

To prove the concept, a simplified instantaneous microwave frequency measurement system shown in Fig.3 is set up. A light wave at 1 564.07 nm generated by a tunable laser source is sent to an MZM which is driven via one RF port by the CW microwave signal from a vector network analyzer (VNA). An erbium-doped fiber amplifier (EDFA) and an ATT are used to control the power of the modulated signal which is divided into two parts at an OC. One part goes into the PD directly and operates as an all-pass response, and the other part enters the RDL loop consisting of an SOA, a TOBF and an OC. The TOBF with a 3 dB bandwidth of 1.2 nm is centered at 1 564.19 nm, detuning from the pump wavelength by about 0.12 nm. The inversely modulated signal is extracted from the ASE by the TOBF and circulates in the loop for realizing a band-pass filter with negative coefficients.

The measured frequency response is shown in Fig.4, and it can be seen that the measurement resolution is different in a given measurement range. This is because the TOBF has a Gaussian shape and a limited rejection ratio. When the central wavelength of the TOBF is detuned from the pump wavelength slightly, the pump signal cannot be suppressed completely by the TOBF. The residual pump signal also realizes a band-pass response with positive coefficients. Moreover, due to the wavelength conversion process in the SOA, the converted signal is delayed slightly relative to the pump signal, and then the time delay of the band-pass filter realized by the converted signal is slightly larger than that realized by the pump signal. Thus, the measured filter response is actually the combination of two band-pass filters with opposite coefficients and different times. The HMPF transfer function can be expressed as

$$H(f_m)=\kappa+\underbrace{\frac{(1-\kappa)^2 g_p e^{-j2\pi f_m T_p}}{1-\kappa g_p e^{-j2\pi f_m T_p}}}_{H_p(f_m)}-\underbrace{\frac{(1-\kappa)^2 g_c e^{-j2\pi f_m T_c}}{1-\kappa g_c e^{-j2\pi f_m T_c}}}_{H_c(f_m)}, \quad (5)$$

where $H_p(f_m)$ and $H_c(f_m)$ represent the transfer functions of the band-pass filter realized by pump signal and the band-pass filter with negative coefficients realized by converted signal, respectively. κ is the coupling coefficient of the optical coupler, and g_p and g_c are the gains of pump signal and converted signal, respectively. T_p and T_c are the corresponding time delays experienced by pump signal and converted signal travelling one round trip, respectively. When the stopband power of the band-pass filter response with positive coefficients is equal to the passband power of band-pass response with negative coefficients, as shown in the inset of Fig.4, a monotonic frequency response varying from positive infinity to negative infinity is obtained. The theoretical and measured transfer functions are shown in Fig.4, and it can be seen that the measured response agrees well with the calculated response.

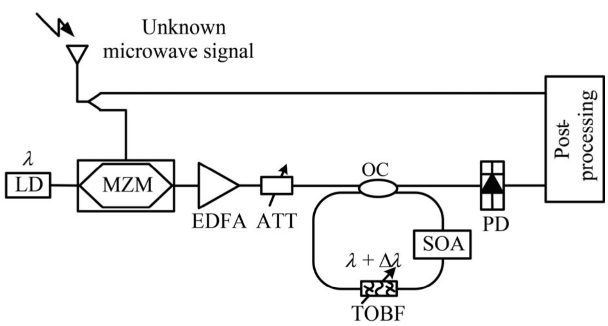

Fig.3 Schematic diagram of experimental setup

The measured frequency compared with the real input frequency is presented in Fig.5, and the measurement error with respect to the actual input frequency is within about 500 kHz as shown in Fig.6. The measurement range depends on the RDL loop length, and the measurement range selected in our experiment is from 2.008 7 GHz to 2.018 7 GHz. Note that since the effective RDL loop length of the band-pass filter is about 10.34 m due to the optical fiber pigtails, a free spectral range (FSR) of 20 MHz is obtained. In practical applications, the loop length should be reduced to increase the measurement range, and a wider measurement range can be achieved through integration. In addition, if an optical variable delay line (OVDL) is inserted into the RDL loop, a tunable measurement range can be achieved.

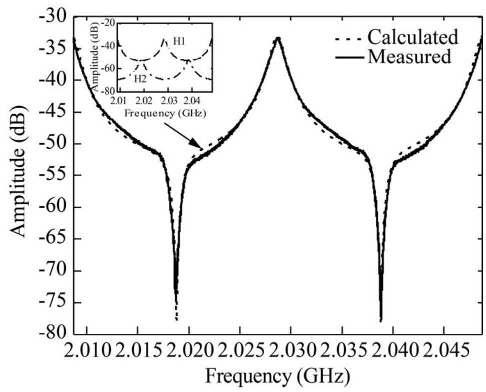

Fig.4 Measured and calculated frequency responses

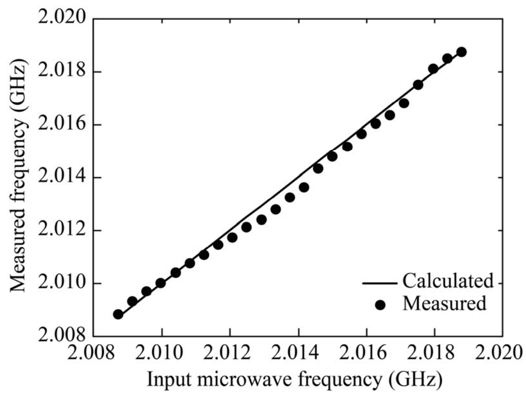

Fig.5 Measured frequency as a function of input frequency

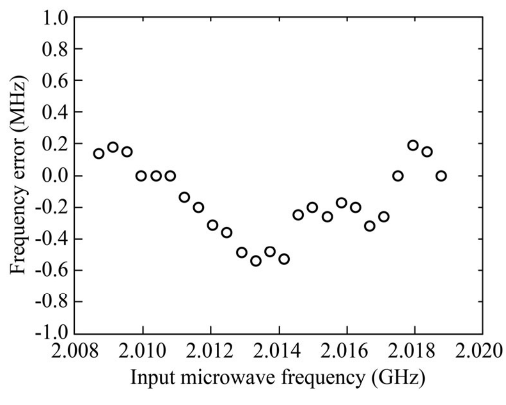

Fig.6 Measurement error versus the input frequency

A novel technique for instantaneous microwave frequency measurement using an HMPF is proposed and experimentally demonstrated. By controlling the power relationship between the all-pass microwave signal and the stopband of the band-pass filter response with negative coefficients, a power transfer function varying from positive infinity to negative infinity is realized. The measurement error within about 500 kHz over a frequency range from 2.0087 GHz to 2.0187 GHz is demonstrated. Due to the infinite power variation, the measurement resolution can be significantly increased. Since only one laser source, one modulator and one PD are needed, the complexity and cost of the system are greatly reduced. In addition, the tunability of the IFM can be achieved if an OVDL is inserted in the RDL loop.

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