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# Broadband and High-Precision Instantaneous Frequency Measurement Using Linearly Frequency-Modulated Waveform and Pulse Compression Processing

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**Abstract:** We propose a broadband and high-precision instantaneous frequency measurement method using linearly frequency-modulated waveform and pulse compression processing. A precision of ±100 MHz is experimentally achieved over a frequency range from 3 to 18 GHz. 
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## 1. Introduction

Instantaneous frequency measurement (IFM) is such a technique to rapidly obtain the frequency of a microwave signal, which is necessary and of great importance in radar, communication, electronic warfare, and cognitive radio systems [1]. The microwave photonics (MWP) technologies, featuring broadband and fast signal processing, are employed to realize the high-performance IFM [2,3]. The MWP-based IFM techniques discriminate the frequency by frequency-to-power, frequency-to-space, or frequency-to-time mapping. The frequency-to-power mapping, which achieves IFM by building an amplitude comparison function (ACF), is a general method, but it suffers from very poor linearity of the ACF and high cost [4,5]. For the technologies based on frequency-to-space mapping, the resolution is limited by the channel spacing of the optical channelizer, and hard to improve [6]. The techniques based on frequency-to-time mapping has a relatively low resolution of 12.5 GHz and a relatively large measurement error of ±1.56 GHz due to the limited dispersion of a dispersive time delay device [7].

In this paper, an IFM method using linearly frequency-modulated waveform and pulse compression processing is proposed and experimentally demonstrated, which owns a broad measurement range and a high measurement precision. The signal-under-test (SUT) is converted into a carrier-suppressed optical double-sideband (CS-ODSB) signal by using a Mach-Zehnder modulator (MZM), which is then combined with an optical linearly frequency-modulated (LFM) signal. As only the +1st-order sideband of the CS-ODSB signal is located in the frequency range of the optical LFM signal, a photocurrent generated by the +1st-order sideband of the CS-ODSB signal and optical LFM signal is obtained by photodetection. After signal sampling and pulse compression processing, the frequency of the SUT is thus discriminated. Benefitting from the employment of the pulse compression processing, the resolution of the proposed method is highly improved compared to the traditional frequency-to-time mapping techniques. In the experiment, a frequency accuracy of ±100 MHz is achieved within a frequency range from 3 to 18 GHz.

## 2. Principle

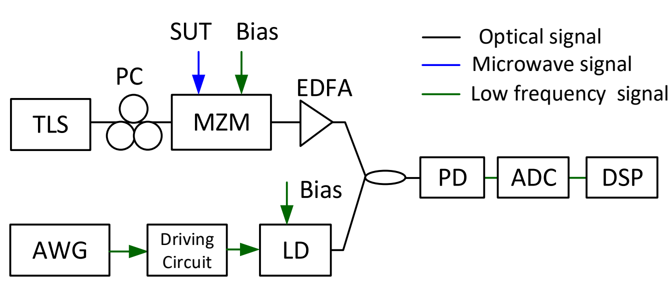


Fig. 1. The schematic diagram for the proposed IFM system. TLS: tunable laser source; PC: polarization controller; SUT: signal-under-test; MZM: Mach-Zehnder modulator; EDFA: erbium-doped fiber amplifier; AWG: arbitrary waveform generator; LD: laser diode; PD: photodetector; ADC: analog-to-digital converter; DSP: digital signal processor.

Figure 1 shows the schematic diagram of the proposed IFM system. A SUT with a frequency of $f_{\mathrm{SUT}}$ is modulated on a lightwave from a tunable laser source (TLS) at an MZM biased at minimum transmission point (MITP). Hence, a CS-ODSB signal is generated, which can be written as

$$E_{\mathrm{SUT}}(t)=E_0J_{-1}(\beta)\exp\left[j2\pi\left(f_0-f_{\mathrm{SUT}}\right)t\right]+E_0J_{+1}(\beta)\exp\left[j2\pi\left(f_0+f_{\mathrm{SUT}}\right)t\right] \tag{1}$$

where $E_0$ and $f_0$ are the magnitude and frequency of the optical carrier, respectively. $J_{\pm}(\bullet)$ represents the $\pm$1st-order Bessel function of the first kind and $\beta$ is the modulation index of the MZM.

In the lower path, a laser diode (LD) is driven by a sawtooth waveform via a driving circuit [8] and an optical LFM signal is thus obtained. The expression in the time domain can be given by

$$s_{\mathrm{r}}(t)=E_{\mathrm{LFM}}\exp\left(j2\pi f_c t+j\pi Kt^2\right)\quad 0\le t\le T \tag{2}$$

where $E_{\mathrm{LFM}}$ is the amplitude of the optical LFM signal and $T$ is the pulse width. $f_{\mathrm{c}}$ and $K$ are respectively the center frequency and the chirp rate of the LFM pulse.

By carefully setting the $f_0$ and $f_{\mathrm{c}}$, only the +1st-order sideband is located in the sweeping range of the LFM signal. Thus, by square-law detection of a photodetector (PD), a photocurrent generated from the +1st-order sideband and the LFM signal is produced. The electrical field of the photocurrent can be mathematically written as

$$i(t)=i_0\exp\left[j\pi Kt^2+j\pi K\Delta t\left(f_{\mathrm{SUT}}\right)t\right]\quad 0\le t\le T_s \tag{3}$$

where $T_{\mathrm{s}}$ is the pulse width of the converted electrical LFM signal. $\Delta t(f_{\mathrm{SUT}})$ is the time delay related to the frequency of the SUT.

To achieve pulse compression processing, a reference waveform generated by beating the optical carrier from the TLS and the LFM signal is premeasured, which is

$$i_{\mathrm{ref}}(t)=i_0\exp\left(j\pi Kt^2+j\pi K\Delta t_0 t\right)\quad 0\le t\le T_s \tag{4}$$

The pulse compression processing is performed, wherein the converted electrical LFM signal is correlated with the reference waveform. By detecting the correlation peak, the frequency of the SUT is thus obtained. Thanks to the narrow pulse width of the optical LFM signal, the measurement speed is fast.

## 3. Experiments and results

A proof-of-concept experiment based on the configuration shown in Fig. 1 is carried out. The TLS emits a 1544.485-nm lightwave with an optical power of 8 dBm. A 20-GHz MZM (JDS Uniphase, Model 10023874) and a 10-GHz PD (Nortel Inc.) followed by a 1.2-GHz lowpass filter are used to achieve electrical-to-optical and optical-to-electrical conversions. An optical LFM signal generator comprises of an electrical arbitrary waveform generator (AWG, Agilent 33250A), a driving circuit [8] and a commercial LD, which produces an optical LFM signal with a pulse width of 20 μs. A real-time oscilloscope (Agilent DSO-X 93204A) is employed to recond the generated photocurrent.

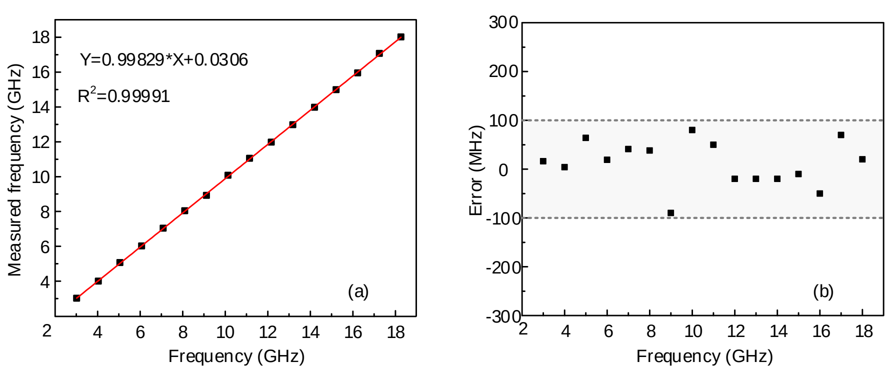


Fig. 2. (a) The experimentally measured results with linear fitting and (b) the measurement errors.

In the experiment, the power of the SUT is set to 19 dBm and the frequency tuning range is from 3 to 18 GHz. Figure 2 shows the experimentally measured results with linear fitting and the measurement errors. As can be seen from Fig. 2(a), the measured frequencies with linear fitting demonstrate high linearity. The R-square is as high as

0.99991. The frequency precision is ±100 MHz over a frequency range from 3 to 18 GHz, as shown in Fig. 2(b). The frequency precision is restricted by the frequency stability of the TLS and the LD. By synchronizing the two optical sources, the frequency precision can be dramatically improved by tens or even hundreds of times. It should be noted that the measurement range cannot be higher due to the limited bandwidth of the 20-GHz MZM. If a high-speed MZM and an optical LFM signal owning a large sweeping range are adopted, a hundred-GHz measurement range is potentially achievable.

## 4. Conclusion

An approach using LFM waveform and pulse compression processing is proposed and experimentally demonstrated which potentially has hundred-GHz measurement range and sub-MHz precision. In the experiment, a frequency precision of ±100 MHz over a frequency range from 3 to 18 GHz is achieved.

## 5. Acknowledgement

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