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基于受激布里渊散射的宽带宽和高精度的微波频率瞬时测量

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摘 要:提出了一种基于受激布里渊散射效应的瞬时频率测量方法.未知信号经过强度调制作为泵浦光,矢量网络分析仪产生的信号经过相位调制作为扫描信号光,当泵浦光和扫描信号光之间满足相位匹配条件时,受激布里渊散射效应发生并实现相位调制到强度调制的转换,未知信号的频率被测量.实验验证可以测量 0.5 GHz-27 GHz 的微波信号的频率,最大误差小于 20 MHz.

关键词:微波光子学;瞬时频率测量;光子微波测量;相位调制;受激布里渊散射

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Instantaneous Microwave Frequency Measurement with Ultra-wide Range and High-resolution Based on Stimulated Brillouin Scattering

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Abstract: A photonic method for instantaneous microwave frequency measurement based on stimulated Brillouin scattering was proposed. The unknown radio frequency signal is modulated by intensity modulator and then it is considered as pump light. The signals generated by vector network analyzer are modulated by phase modulator and then they are considered as sweeping signal light. When the phase matching condition is satisfied between pump light and sweeping signal light, the stimulated Brillouin scattering occurs and the conversion from phase modulation to intensity modulation selectively is achieved. The frequency of unknown radio frequency signal is ultimately measured. Experimental results demonstrate that the measurement ranges from 0.5 GHz to 27 GHz and the maximum measurement error is less than 20 MHz.

Key words: Microwave photonics; Instantaneous frequency measurement; Photonic microwave measurement; Phase modulation; Stimulated Brillouin scattering

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0 Introduction

In modern radar and electronic warfare systems, the measurement of frequency to an unknown microwave signal is important. But conventional approaches are based on electrical technology, which are

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not meeting with modern needs gradually due to their inherent disadvantages, such as limited bandwidth, high loss and electromagnetic interference. Meanwhile, optical technology has attracted extensive attention for its advantages, such as ultra-wide measurement range, low loss, light weight and immunity to electromagnetic interference. Over the past few decades, some approaches were proposed[1-14]. These measurement methods can be divided into three categories i.e., fiber dispersion-induced power-fading functions[1-7], four-wave mixing[8-10] and Stimulated Brillouin Scattering (SBS)[11-14]. Among the schemes based on power-fading functions, one or sevaral frequency-dependent Amplitude Comparison Functions (ACFs) are constructed. In Ref.[1], a single ACF is used to estimate the microwave frequency. Although the measurement range can be adjusted by changing the length of fiber, the measurement resolution is small because of the flat ACF curve. In order to overcome the shortcoming, several ACFs with a large slope are constructed simultaneously[2-6]. Three ACFs are produced by using three sections of fiber[2]. There are two more lasers in Ref.[3] compared with the scheme in Ref.[2]. A Polarization Modulator (PolM) is applied in Ref.[4-6]. The polarization state is adjusted by tuning the bias voltage applied to the PolM[4-5]. Then the notch point of ACF is shifted and the slope of ACF is enlarged. In Ref.[6], several ACFs are constructed by using multiple photonic links. The measurement resolution is improved by the selection of ACF which has the large slope. Although the method mentioned in Ref.[7] can also reduce measurement error by adjusting the polarization state, the author discards the accuracy for the sake of simple construction and large measurement range. The measurement error reached ±0.3 GHz over the range of 1.6 GHz-24.6 GHz. The schemes using multiple power-fading functions generally achieve a frequency measurement range of 20GHz and a measurement resolution of 100 MHz[2-6].

Several Instantaneous Microwave Frequency Measurement (IMFM) systems using four-wave mixing were proposed[8-10]. These approaches achieve a high frequency measurement range from 1 GHz to 40 GHz. The approach[8] does not require high-speed electronics at any stage which is a competitive advantage. In Ref.[9], a new scheme which extends the system of Ref.[8] is proposed. An additional High Nonlinear Optical (HNLF) is used to cope with the input signal onto a second optical wavelength. The key advantage of the scheme over the scheme of Ref.[8] is copier stage. The IMFM system of Ref.[10] differs from the previous. It realizes IMFM using four-wave mixing in a chalcogenide chip. This reduces measurement latency compared to fiber-based approaches. The other advantage is that it can be used for integrated components. The shortcoming of the systems using four-wave mixing is that measurement error is large. The measurement error is ±250 MHz in Ref.[8-10]. The other nonlinear effect, SBS is also applied to IMFM[11-14]. In Ref.[11], SBS is used to tune ACF in order to adjust measurement range and resolution. It can achieve conversion of frequency between a measurement range (~2 GHz) with high resolution (±0.05 GHz) and a fixed measurement range (12 GHz) with resolution (±0.25 GHz). The frequency measurement range of the method in Ref.[12] can be very large, and the measurement range mainly depends on the bandwidth of other devices. This instantaneous frequency measurement system take advantage of wavelength dependence of Brillouin gain to construct an ACF. However, Brillouin frequency shift is small in the measurement range of dozens of GHz, so the accuracy is not very high and the requirements of system stability are high. The other scheme which has a capacity of measuring multiple microwave signals is proposed[13]. The main idea is the conversion from phase modulation to intensity modulation selectively using SBS. The scheme can achieve a measurement range of 9 GHz with resolution of 30 MHz. In Ref.[14], the measurement range for multiple microwave signals with multiple frequencies is four times Brillouin frequency shift. It is proved by numerical simulation.

In this paper, an approach for IMFM with ultra-wide measurement range and high-resolution is proposed. The main idea of this method is to selectively gain or attenuate the amplitudes of phase modulated signal via SBS. Then the amplitude of upper side-band is different from lower side-band. As a result, the conversion from phase modulation to intensity modulation selectively is achieved. Then the frequency of an unknown microwave signal is obtained.

2 Principle of operation

Under small signal modulation, it is merely considered to the optical carrier and the two first-order sidebands for an optical phase modulated signal. The output optical field of Phase Modulator (PM) driven by a RF signal can be expressed as follows

$$E(t)=J_0\cos(w_0 t)+J_1\cos\left[(w_0+w_m)t+\frac{\pi}{2}\right]-J_1\cos\left[(w_0-w_m)t-\frac{\pi}{2}\right] \tag{1}$$

where w_0 is the light carrier frequency, w_m is the RF signal frequency, J_n represents the nth-order Bessel function ($n=0,1$). It can be seen from Eq.(1) that the amplitudes of the upper and the lower side-band are equal and their phases are opposite. They will be offset completely in photodetector (PD). The main idea of the proposed scheme is to change that through SBS.

The system of the proposed approach for IMFM is showed in Fig. 1. The continuous wave light from tunable laser is split into two paths by an optical coupler. In the upper path, the light modulated by PM. The modulation signal is a series of sweeping microwave signals f_s from Vector Network Analyzer (VNA). The modulated optical signals access to HNLF in which SBS occurs. An optical isolator (ISO) follows by the PM for isolating the signals from HNLF. In the lower path, the optical wave is modulated by an unknown RF signal f_x via a Mach-Zehnder Modulator (MZM). In this scheme, carrier suppressed double sideband (DSB-SC) signal is obtained by applying a bias voltage into the MZM. Then the DSB-SC signal is amplified by an Er-Doped Fiber Amplifier (EDFA). The output of EDFA which is regarded as pump light is accessed to HNLF via an Optical Circulator (OC). As is shown in Fig. 1, the DSB-SC signal enters the OC from port 1 and outputs from the port 2 to HNLF in where the DSB-SC signal interacts with the phase modulated signals. The transmitted signals are finally detected by a PD. Then they are injected into VNA.

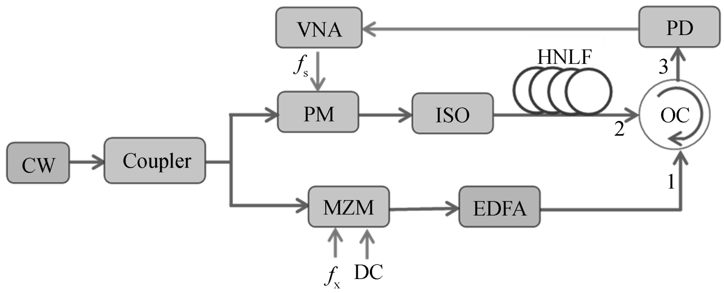


Fig.1 Principle of operation of the proposed IFM approach based on SBS

The process of SBS is illustrated in Fig. 2. The Fig. 2 (a) shows the DSB-SC signal with an unknown RF signal. The optical field of DSB-SC signal can be expressed as follows

$$E(t)=2J_1\{\exp[\mathrm{j}2\pi(f_c+f_x)t]+\exp[\mathrm{j}2\pi(f_c-f_x)t]\} \tag{2}$$

where f_c represents the light carrier frequency, f_x represents the frequency of unknown RF signal to be measured and it is bigger than the Brillouin frequency shift f_b, J_1 represents the 1th-order Bessel function. The f_x represents the frequency of RF signal to be measured and it is bigger than the Brillouin frequency shift f_b. The DSB-SC signals are regarded as pump light. The Fig. 2 (b) shows sweeping signals f_s. They are generated by PM and are regarded as Stokes light. The optical field of sweeping signals can be expressed as follows:

$$E(t)=J_0\exp(\mathrm{j}2\pi f_c t)+J_1\exp\left\{\mathrm{j}\left[2\pi(f_c+f_s)t+\frac{\pi}{2}\right]\right\}-J_1\exp\left\{\mathrm{j}\left[2\pi(f_c-f_s)t-\frac{\pi}{2}\right]\right\} \tag{3}$$

where f_s represents the frequency of sweeping signals, J_n represents the nth-order Bessel function ($n=0$, 1). In this proposed scheme, the phase modulated signals and the DSB-SC signal counter-propagate in HNLF. When the frequency between the DSB-SC signal and the sweeping signals differs by a Brillouin frequency shift f_b, SBS occurs. The phase modulation signal is affected by stimulated Brillouin scattering, and the optical field can be expressed as follows:

$$E(t)=\exp(\mathrm{j}2\pi f_c t)\left\{J_0+J_1\exp\left\{g(f_x-f_b-f_s)+a(f_x+f_b-f_s)+\mathrm{j}\left[2\pi(f_c+f_s)t+\frac{\pi}{2}\right]\right\}-\right.$$
$$\left.J_1\exp\left\{g(f_s-f_b-f_x)+a(f_s+f_b-f_x)+\mathrm{j}\left[2\pi(f_c+f_s)t+\frac{\pi}{2}\right]\right\}\right\} \tag{4}$$

where $g(f)$ and $a(f)$ denote Brillouin gain and loss. They can be expressed as

$$g(f)=\frac{g_0}{2}\frac{\left(\frac{\Delta V_B}{2}\right)^2}{f^2+\left(\frac{\Delta V_B}{2}\right)^2}+\mathrm{j}\frac{g_0}{4}\frac{\left(\frac{\Delta V_B}{2}\right)f}{f^2+\left(\frac{\Delta V_B}{2}\right)^2} \tag{5}$$

$$a(f)=-\frac{g_0}{2}\frac{\left(\frac{\Delta V_B}{2}\right)^2}{f^2+\left(\frac{\Delta V_B}{2}\right)^2}-\mathrm{j}\frac{g_0}{4}\frac{\left(\frac{\Delta V_B}{2}\right)f}{f^2+\left(\frac{\Delta V_B}{2}\right)^2} \tag{6}$$

where $g_0=g_B I_P L_{eff}/A_{eff}$, and ΔV_B is the Brillouin linewidth, g_B is line center gain, I_P is power of pump light, f is the frequency detuning relative to the center of gain or loss spectrum, L_{eff} and A_{eff} are effective fiber length and effective mode area of HNLF, respectively. The Fig. 2 (c) shows the process. The sweeping signals at f_c+f_{s1} and f_c-f_{s2} are amplified respectively by the pump lights at f_c+f_{x1} and f_c-f_{x2}. At the same time, the sweeping signals at f_c+f_{s2} and f_c-f_{s1} are attenuated due to the Brillouin loss spectrum. When f_x is less than f_b, the process of SBS is shown in Fig. 2 (d). In both cases, we can observe two peaks on VNA. The first peak is generated by the beating between f_c and $f_c\pm f_{s1}$. And the second peak is generated by the beating between f_c and $f_c\pm f_{s2}$. It can be found that there is a constant difference in frequency between the unknown signal and the second peak observed on VNA. So the frequency of unknown RF signal can be calculated and the frequency is equal to $f_{s2}-f_b$. The main advantage for the proposed scheme is that it can realize a frequency measurement with ultra-wide measurement range and high-resolution. The measurement range is decided by the scanning range of VNA and the modulation frequency range of modulators. If they are large enough, we can get a higher measurement range of unknown signal with high resolution.

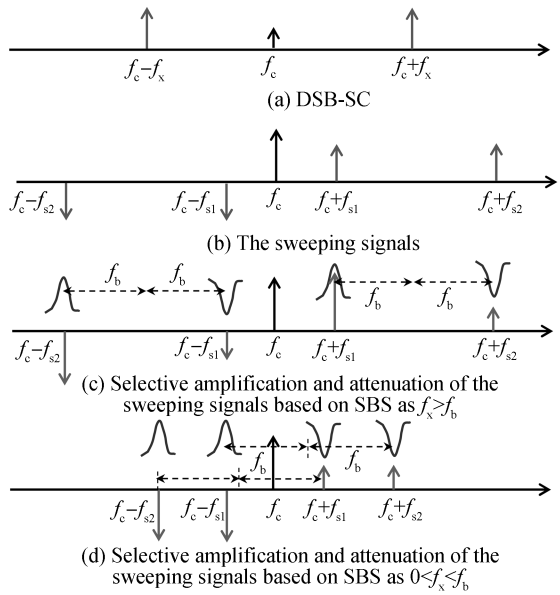
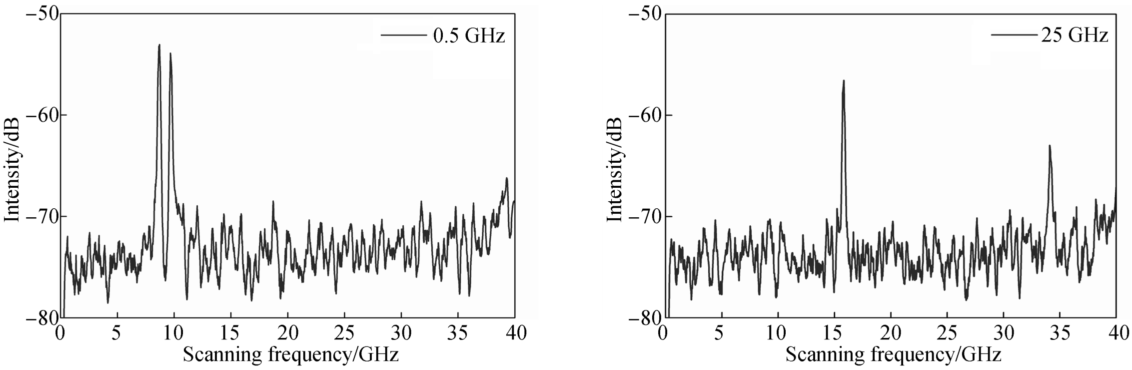


Fig.2 Optical spectra evolvement of the selective conversion of PM to AM based on SBS

3 Experimental results and discussion

The optical link of experiment setup is shown in Fig.1. The laser wavelength from the tunable laser (Santec TSL-510) is 1 550 nm. Then the light is split into two paths by a 5 ∶ 5 optical coupler. The light in upper path is sent to the PM. A series of sweeping signals with the sweep range from 0.04 GHz to 40 GHz which are generated by the VNA (Anritsu 37269C) are applied to the PM. Then the phase modulated signals are launched into a 1.0 km HNLF after an ISO. In the lower path, the light is sent to the MZM. An unknown RF signal generated by the PSG analog signal generator (Keysight E8257D) is launched into the MZM. At the same time, the bias voltage produced by a DC stabilized power supply is applied to the MZM to realize DSB-SC modulation. The bias voltage is the key to eliminate interference from carrier. Then the modulated optical signal is amplified by an EDFA and enters the HNLF via an OC. The Brillouin frequency shift of the HNLF is 9.205 825 GHz when the wavelength of pump light is 1 550 nm. The final optical signals are converted to electrical signals through a PD (Tektronix SD-48) after occurrence of SBS. We can calculate the frequency of unknown RF signal through the formula $f_x=f_{s2}-f_b$. The f_{s2} is frequency of the second crest on VNA.

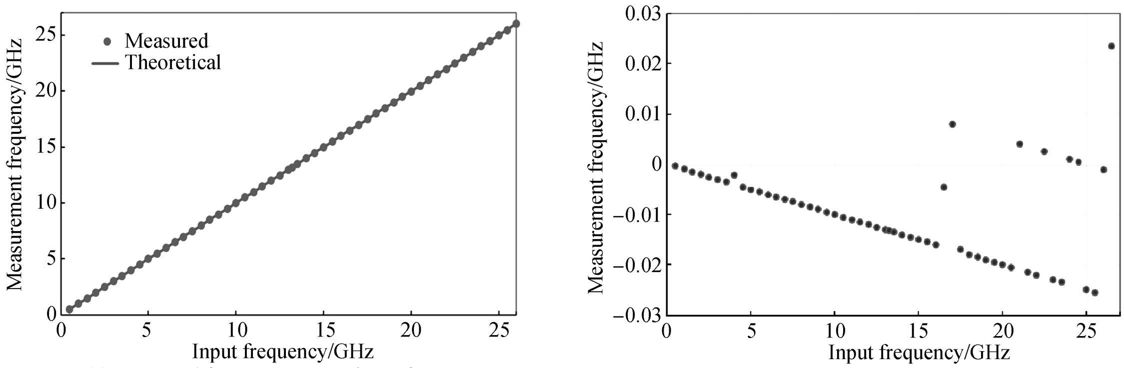
The experimental results are shown in Fig. 3. There are two wave creases observed on VNA. The second peak becomes blurred when the frequency of unknown RF signal is high. This is attributed to the bandwidth constrains of MZM and PM. It is one of the keys to the frequency measurement range.



(a) The frequency of unknown RF signal f_x=0.5 GHz (b) The frequency of unknown RF signal f_x=25 GHz

Fig.3 Experimental pictures

The relationshipbetween measurement frequencies and input frequencies is shown in Fig. 4 (a). It can be seen that the measurement frequencies are consistent with the input frequencies excellently in the frequency range of 0.5 GHz-27 GHz. The measurement errors are illustrated in Fig. 4 (b) and the maximum error is less than 30 MHz. This is one of the advantages of this proposed method. In addition, it can been seen from Fig. 4 (b) that the measurement error increases linearly as input frequency. It results from Brillouin frequency shift which declines linearly with increase of optical wavelength Ref.[15]. In this proposed method, Brillouin frequency shift is measured by experiment, but the measurement accuracy is not high due to constraints of experimental conditions. So the measurement range is divided into two parts, namely 0.5 GHz-14 GHz and 14 GHz-27 GHz. The Brillouin frequency shift in two measurement intervals is 9.204 GHz and 9.199 GHz, respectively. The frequencies of unknown RF signals is calculated according to the new Brillouin frequency shifts.



(a) Measured frequency versus input frequency (b) Measured errors

Fig.4 Experimental results

The measurement error is shown in Fig. 5. The measurement error reduced from 30 MHz to 20 MHz.

In the course of experiment, the power of unknown RF signal has little effect on the measurement error. When the frequency of unknown RF signal are 1 GHz, 11 GHz and 20 GHz, the power gradually reduced from 20 dBm to 6 dBm with 2 dBm step. Then the frequency of unknown RF signal is measured and measurement error is calculated. The measurement errors are shown in Table 1.

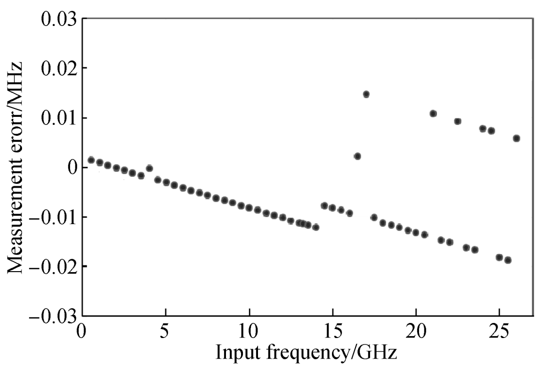


Fig.5 The measurement error after changing the Brillouin frequency shift

Table 1 The measurement error corresponding different power of the unknown RF signal

Frequency	20 dBm	18 dBm	16 dBm	14 dBm	12 dBm	10 dBm	8 dBm	6 dBm
1 GHz	4.825 MHz	4.825 MHz	4.825 MHz	4.825 MHz	−18.15 MHz	4.825 MHz	−18.15 MHz	4.825 MHz
11 GHz	−5.175 MHz	−5.175 MHz	−5.175 MHz	19.8 MHz	−5.175 MHz	19.8 MHz	−5.175 MHz	19.8 MHz
20 GHz	10.8 MHz	10.8 MHz	10.8 MHz	−14.175 MHz	−14.175 MHz	−14.175 MHz	−14.175 MHz	−14.175 MHz

As can be seen from Table 1, the measurement error is still less than 20 MHz. On the other hand, the power of laser would affect the bandwidth of Brillouin gain spectrum, which in turn affects measurement resolution. When the power of laser reduce from 15 mv to 10 mv, the bandwidth of Brillouin gain spectrum increases. The resolution changes from 5 MHz to 8 MHz when the frequency of unknown RF signal is 1 GHz. So the power of laser is as high as possible while ensuring that each device is working properly. And high power can also eliminate the effect of noise. In this paper, the noise in optical link has little effect on measurement result, as long as stimulated Brillouin scattering occurs. When the power of laser is larger, stimulated Brillouin scattering becomes more obvious. Then the effect of noise on optical link is smaller.

In this proposed method, the stability of optical link should be ensured. The wavelength jitter of laser will make Brillouin frequency shift variable, and then the measurement error would be introduced theoretically. Although the change of Brillouin frequency shift is generally small because of the wavelength jitter, the stability of optical link should be ensured to reduce measurement error.

4 Conclusion

An approach for instantaneous microwave frequency measurement based on SBS is proposed and experimentally demonstrated. The key of the approach is the conversion from phase modulation to intensity modulation selectively. It is realized by SBS. The experimental results demonstrate that the measurement error is smaller than 20 MHz in the frequency range of 0.5 GHz-27 GHz. And the measurement range can be extended by improving the scanning range of VNA and the modulation frequency range of modulators.

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