Tunable photonic microwave generated by multi-wavelength Brillouin fiber laser

Wang Rugang[1,2] Zhang Xinran[1] Zhao Li[1] Zhang Xuping[3]

([1]Key Laboratory of Underwater Acoustic Signal Processing of Ministry of Education, Southeast University, Nanjing 210096, China)
([2]College of Information Engineering, Yancheng Institute of Technology, Yancheng 224051, China)
([3]Institute of Optical Communication Engineering, Nanjing University, Nanjing 210093, China)

Abstract: Aimed at the problem of narrow tunability and low frequency microwave signal generated by the optical method, a novel approach to stabilizing the tunable photonic microwave generated by the multi-wavelength Brillouin fiber laser is proposed and is experimentally demonstrated. A single-longitudinal-mode Brillouin fiber laser is designed, and by using the laser, a multi-wavelength Brillouin fiber laser with more than eleven orders of Stokes wave is observed. The wavelength spacing of the adjacent Stokes wave is 0.085 nm. If the Brillouin pump power is increased, the number of Stokes wave output can be further increased. The tunable microwave signals of 10.8 and 21.6 GHz are obtained by heterodyning the Rayleigh wave and Stokes wave of the multi-wavelength Brillouin fiber laser. In the experiment, by tuning the pump wavelength and temperature of the gain fiber, microwave signals at different frequencies are generated. The tunable frequency range can be further expanded by using a temperature controller with a wider adjustment range, and the generated microwave signal exhibits high stability on frequency.

Key words: Brillouin frequency shift; ring laser; multi-wavelength; microwave signal

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The tunable microwave signal generated by the photonic approach has attracted much attention due to its important applications in communication systems, wireless access networks, radar and modern instrumentation[1]. Several effective approaches have been proposed to obtain a tunable microwave signal in the past few decades[2–14], most of which focused on the external modulation solution with a modulator[2–5], optoelectronic oscillator[9], optical beating method[6–9] or dual-wavelength laser[10–11]. In the external modulation solution, a continuous optical wave is directly modulated by the electro-optical modulator (EOM) or the phase modulator (PM), and then the high frequency microwave signal can be obtained via the up-conversion of a low frequency signal. However, a high-quality microwave signal source and a high-speed modulator is required. When the optical beating method is used, two optical wave signals are heterodyned on a photo-detector, and the frequency difference of the optical wave signals is the intended microwave signal. If independent lasers are used to generate the microwave signal by this method, the random phase difference between the lasers will produce high phase noise. Therefore, several effective approaches have been proposed to reduce phase noise, such as using a phase-locked loop[6–7] or multi-wavelength laser[8]. A high-speed modulator is also needed in the optoelectronic oscillator, but the tunablity of the optoelectronic oscillator is limited due to the modulation bandwidth. Stimulated Brillouin scattering (SBS) is the interaction between incident light and phonons within a fiber, and it has been widely used in microwave signal generation. The optical beating method used to obtain the microwave signal based on SBS is considered to be an effective and mainstream scheme due to its low phase noise[12–14].

In order to obtain the microwave signal with wide frequency tunable ranges, a novel approach to stabilizing the tunable photonic microwave generated by the multi-wavelength Brillouin fiber laser (MW BFL) based on the Brillouin amplification technology is proposed and demonstrated in this paper. First, a single-longitudinal-mode Brillouin ring cavity laser is obtained, and then a multi-wavelength Brillouin laser with eleven orders of Stokes wave is observed by using the Brillouin ring cavity laser. The high quality microwave signal can be obtained by heterodyning Rayleigh wave and Stokes wave from the multi-wavelength Brillouin fiber laser.

1 Experimental Setup

The experimental setup using the multi-wavelength Brillouin fiber laser to obtain the tunable microwave signal is schematically shown in Fig. 1. The schematic dia-

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Biographies: Wang Rugang (1975—), male, doctor, associate professor; Zhao Li (corresponding author), male, doctor, professor, zhaoli@seu.edu.cn.

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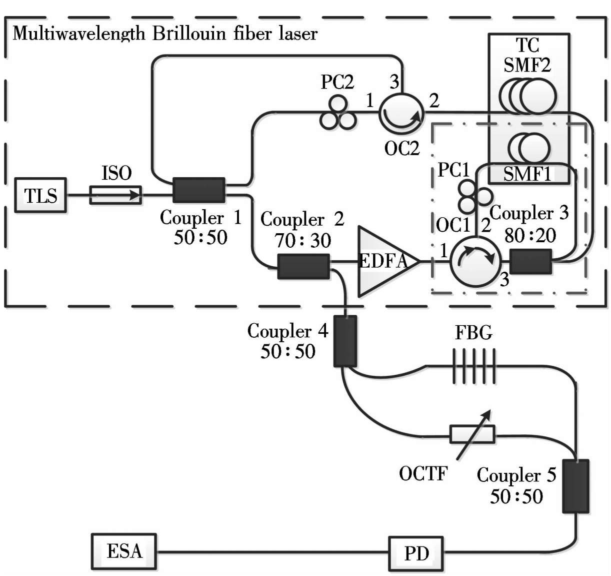
gram of the multi-wavelength Brillouin fiber laser is shown in the dashed box, which contains a tunable laser source (TLS), fiber polarization controllers (PC1, PC2), an erbium-doped fiber amplifier (EDFA), Coupler 1 (50:50), Coupler 2 (70:30), Coupler 3 (80:20), an isolator (ISO), optical circulators (OC1, OC2), and single mode fibers (SMF1, SMF2). The linewidth of the TLS is approximately 200 kHz, and the beam from the port of Coupler 1 is amplified by the EDFA after passing through the 30% port of Coupler 2, and it is used as the Brillouin pump signal in SMF1. The Brillouin ring cavity laser can be obtained in the second ring cavity as shown in Fig. 1, which consists of OC1, Coupler 3, SMF1 and PC1. The Brillouin laser is exported from the 20% port of Coupler 3, which is used as the signal light. The length of the SMF1 is about 4 m, and the total length of the ring cavity is 5. 3 m. The beam from another port of Coupler 1 is injected into SMF2 of 20 km in length via OC2, which is used as the Brillouin pump for SMF2. In SMF2, when the Stokes wavelength excited by this Brillouin pump is aligned with the signal wavelength from the 20% port of Coupler 3, this signal will be amplified. The amplified optical signal is injected into Coupler 1 through OC2. The type of SMF2 is the same as that of SMF1, that is, the Stokes wavelength is equal to the signal light wavelength from the 20% port of Coupler 3. Moreover, the temperature controller (TC) is used to control the temperatures of SMF1 and SMF2. An ISO is used to prevent signal light from traveling into the TLS. Then, the Stokes signal is re-amplified as the pump signal of the next order of Stokes wave, which can be amplified in SMF2.



TLS—tunable laser source; PC—polarization controller
EDFA—erbium-doped fiber amplifier; ISO—isolator
SMF—single mode fiber; FBG— fiber Bragg grating
OCTF—optical channel tunable filter; PD—photo-detector
OC—optical circulator; ESA—electrical spectrum analyzer

Fig. 1 Experimental setup

Two of these signals must be selected to generate the microwave signal. When the narrow bandwidth filters are used, the output signal from the 30% port of Coupler 2 is separated by Coupler 4 (50 : 50). One signal passes through the FBG filter, and the other one passes through an optical channel tunable filter (OCTF). The 3 dB bandwidth of the FBG and OCTF is approximately 0. 1 and 0. 01 nm, respectively. The beating signal is detected by a photo-detector (PD) after passing through Coupler 5 (50:50). The microwave signal is measured by an electrical spectrum analyzer (ESA).

2 Results and Discussion

The transmission direction of the Brillouin pump and Stokes wave is clockwise and counterclockwise as shown in Fig. 1. The mode spacing of the Brillouin laser is controlled by the length of the ring cavity. As shown in Fig. 2, the mode spacing of the Brillouin ring cavity laser can be detected by direct measuring the signal of the Brillouin ring cavity laser, which is approximately 19 MHz. Meanwhile, the extinction ratio is approximately 18 dB between the modes, which can force the laser to operate in the single longitudinal mode due to the mode competition between modes[10].

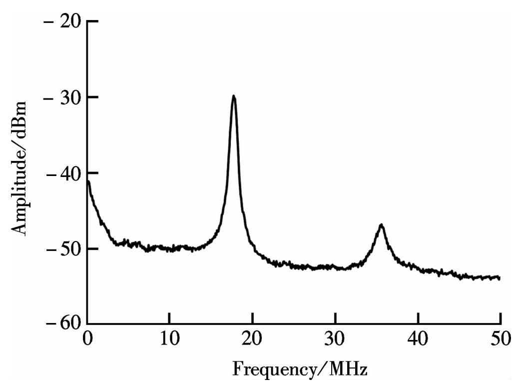


Fig. 2 Mode spacing of the Brillouin ring cavity laser

In the experiment, the type of SMF2 is the same as that of SMF1, and the wavelength of the Brillouin ring cavity laser from the 20% port of Coupler 3 is equal to the Stokes wavelength of SMF2. As a result, the signal from the Brillouin ring cavity laser shown in the small dashed box in Fig. 1 can be amplified. This Brillouin fiber amplifier can be used to amplify any signal. Therefore, the multi-order Stokes signal can be obtained by using the Brillouin fiber amplifier. The effective length of the SMFs is expressed as $L_{\text{eff}} = \frac{1}{\alpha}[1 - \exp(-\alpha L)]$. Here, α is the total fiber loss while L is the length of the fiber. From the equation of the effective length, the maximum effective length of the SMFs is about 21 km, so an SMF2 of 20 km in length is used in the experiment.

When the power of TLS is 1 dBm, the output power of the EDFA is 30 dBm, and the spectrum of the MW BFL is obtained, as shown in Fig. 3. From Fig. 3, the pump wavelength is approximately 1 549. 96 nm, while more than eleven orders of the Stokes wave can be observed, and the wavelength spacing is approximately 0. 085 nm. A great number of output Stokes lines will be obtained if the Brillouin pump power is increased in SMF2. In the experiment, the FBG and OCTF are used to generate the desired signal as shown in Fig. 1. The output spectrum of the OCTF is shown in Fig. 4, it can be seen that the range of tunable wavelength is from 1 549. 66 to 1 550. 08 nm, and the OCTF can be used to select the desired Stokes wave.

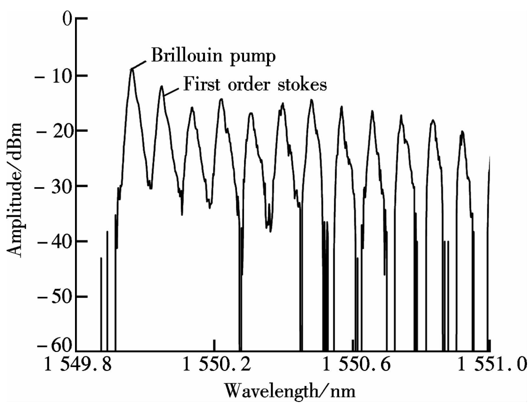


Fig. 3 Spectrum of the multi-wavelength Brillouin fiber laser

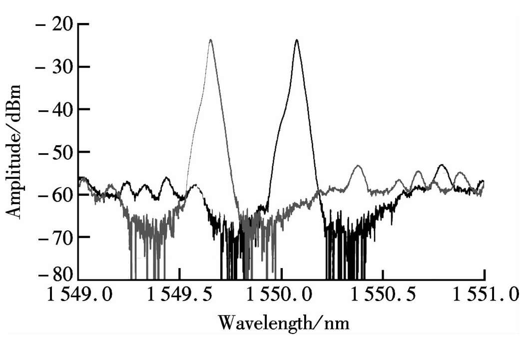


Fig. 4 Output spectrum of the OCTF

The center wavelength of FBG is set to be 1 549. 96 nm, which is the Brillouin pump wavelength. When we tune the OCTF to make the center wavelength, a microwave frequency of 10. 8 and 21. 6 GHz will be generated. Fig. 5 shows that the experimental electrical output signal can be measured by the ESA. Due to the lack of high bandwidth ESA and PD, only a 21. 6 GHz microwave signal is observed. In the Brillouin ring cavity laser, the combined influence of the cavity feedback and the acoustic damping can lead to the narrowing linewidth effect, and the linewidth of the Brillouin ring cavity laser is given by[10]

$$\Delta f_{\mathrm{Stokes}} = \frac{\Delta f_{\mathrm{pump}} (c \ln R)^2}{(c \ln R - nL\pi \Delta \nu_B)^2} \tag{1}$$

where Δf_{pump} is the linewidth of the Brillouin pump; c, R and n are the light velocity in vacuum, the coupling ration of the cavity and the fiber effective index, respectively; L is the length of the cavity. In this experiment, the length of the cavity is approximately 5. 3 m. It can be seen from Eq. (1) that the linewidth of the Brillouin ring laser will decrease when the coupling ration of the cavity is increased. Moreover, the noise of the amplified spontaneous emission (ASE) is very low when the feedback magnifying mechanism is outside the ring cavity[13]. Therefore, a Brillouin ring cavity laser with narrow linewidth can be obtained.

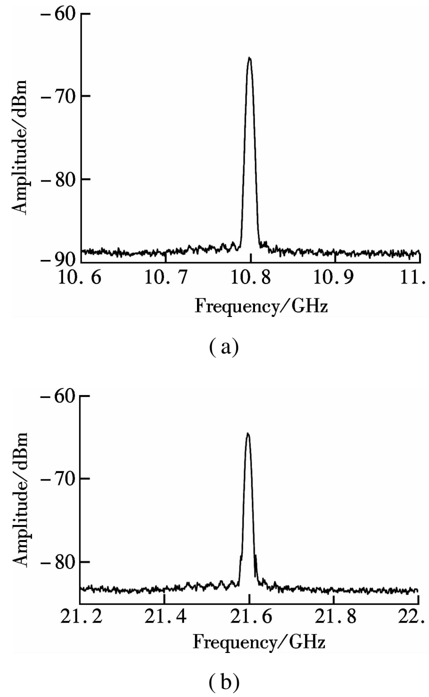


Fig. 5 Spectrum of the microwave signal. (a) Low frequency signal; (b) High frequency signal

The Brillouin frequency shift ν_{B} is expressed as[13]

$$\nu_{\mathrm{B}} = \frac{2nV_{\mathrm{a}}}{\lambda_{\mathrm{B}}} \tag{2}$$

It can be seen from Eq. (2) that the Brillouin frequency shift is inversely proportional to the pump wavelength. The microwave frequency based on the first-order Stokes wave is measured under different pump wavelengths as shown in Fig. 6. The microwave frequency decreases with the increase in the pump wavelength, and therefore, the microwave frequency can be changed by tuning the pump

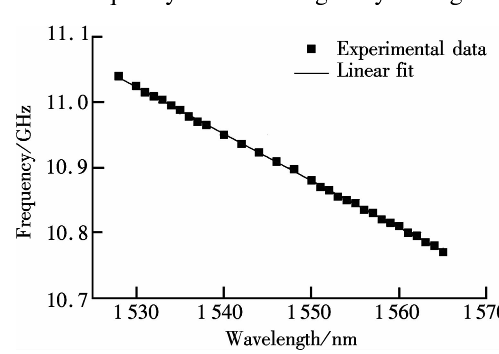


Fig. 6 Microwave frequency under different pump wavelengths

wavelength. The frequency can be tuned from 10.76 to 11.043 GHz when the pump wavelength tunes are from 1 565 to 1 528 nm.

When the temperature changes, the refractive index and the speed of light in the optical fiber will be changed, and the Brillouin frequency shift can be expressed as[13]

$$\nu_B(T) = \nu_B(T_r) + C_T(T - T_r) \quad (3)$$

where T_r and C_T are the reference temperatures and Brillouin frequency shift coefficients, respectively. It can be seen from Eq. (3) that the Brillouin frequency shift can be tuned by changing the temperature. The frequency of the generated microwave signal at different temperatures with a pump wavelength of 1 528 nm is shown in Fig. 7. It can be seen that the high frequency signal can be obtained if high temperatures are used. The slop of the line is approximately 0.93 MHz/℃. The tunable range of the frequency can be further increased by using a temperature controller with a wide adjustment range.

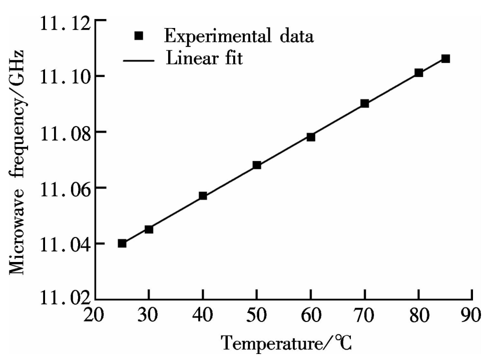


Fig. 7 Measured microwave frequency at different temperatures

In the experiment, only the tunable microwave frequency using the first-order Stokes wave is demonstrated by changing the pump wavelength and temperature. However, the tunable microwave signal can also be obtained by using other order Stokes waves. The frequency of generated microwave signal is equivalent to multiples of Brillouin frequency shift from the MW BFL, which can be expressed as[12]

$$f_{RF} = N\nu_B = N\frac{2nV_a}{\lambda_p} \quad (4)$$

It can be seen from Eq. (4) that the pump wavelength fluctuation is the main factor causing frequency stability. In the experiment, the TLS (Agilent lightwave measurement system 8164B) is used as the Brillouin pump and its wavelength fluctuation is very small. Therefore, the frequency stability of the generated microwave signal can be greatly ensured. The frequency stability of the third-order Stokes wave is measured at time intervals of 20 min, as plotted in Fig. 8. It can be seen from Fig. 8 that the frequency fluctuation is approximately 0.3 MHz in 2 h, so the microwave signal has good frequency stability. Limited by the measuring equipment of the signal source analyzer, the phase noise of the microwave signal is not measured. The phase noise of the Brillouin pump is transferred to the Brillouin lasing light after being significantly reduced due to the influence of the acoustic damping and the cavity feedback[14]. So, the generated microwave signal may suffer from low phase noise.

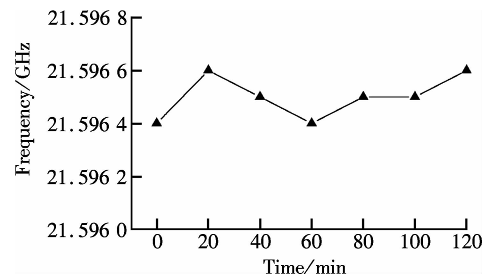


Fig. 8 Frequency stability of microwave signal with 21.6 GHz within 120 min

3 Conclusion

In this paper, a novel solution to obtain a tunable microwave signal is proposed and it is experimentally demonstrated by using MW BFL. More than eleven orders of Stokes wave are obtained. More and more output Stokes lines can be observed, if the EDFA is used to enhance the pump power. The microwave signal is obtained by a heterodyning multi-order Stokes wave. The microwave frequency can be adjusted by tuning the pump wavelength and temperature of the fiber. The microwave signal with the range of 11 to 21.6 GHz is obtained, and the generated microwave signal exhibits high frequency stability.

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多波长布里渊激光器产生的可调谐微波信号

王如刚[1,2] 张昕然[1] 赵 力[1] 张旭苹[3]

([1] 东南大学水声信号处理教育部重点实验室, 南京 210096)
([2] 盐城工学院信息工程学院, 盐城 224051)
([3] 南京大学光通信工程研究中心, 南京 210093)

摘要: 针对光学方法产生的微波信号具有调谐范围窄和频率低等问题,提出并实验验证了一种通过多波长布里渊激光器来产生稳定可调谐微波信号的方法. 设计了一种单纵模布里渊激光器,利用该单纵模布里渊激光器获得了超过 11 阶斯托克斯波的多波长激光器,其波长间隔为 0.085 nm,如果继续增加布里渊泵浦功率,输出的斯托克斯波数量可进一步增加;通过差频瑞利散射信号和多波长激光器信号,获得了中心频率为 10.8 和 21.6 GHz 的微波信号,在实验中,通过调节泵浦波长和增益光纤的温度,产生了不同频率的微波信号. 如果使用较宽温度调节范围的温度控制器可增加调谐范围,且获得的微波信号具有较高的频率稳定性.

关键词: 布里渊频移;环形腔激光器;多波长;微波信号

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