光学学报

基于受激布里渊散射的可调谐稳定光电振荡器

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摘要 如何获得频率高、相位噪声低和稳定性高的微波信号一直都是微波光子学领域的研究热点。基于此，提出一种基于受激布里渊散射(SBS)的可调谐光电振荡器(OEO)。实验中光载波和泵浦光来自同一可调谐激光器，利用泵浦光的SBS对光载波的相位调制边带进行放大，通过改变可调谐激光器的输出波长使布里渊频移量发生变化，从而实现输出微波信号的可调谐。实验结果表明，所设计的OEO可以实现频率范围为10.13～10.65 GHz的信号输出，可调谐范围为520 MHz。结构中仅使用了一个相位调制器，无偏压输入器件的引入，这使得所设计的OEO稳定性较高。在20 min内频率漂移小于1 MHz，功率变化小于1.15 dB。

关键词 光学器件；光电子学；微波光子学；受激布里渊散射；光电振荡器；频率可调谐
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1 引　　言

稳定性高、相位噪声低的微波信号已经广泛应用于通信、仪器仪表测试、天文探测及高性能的雷达系统等领域[1-3]。传统的微波源主要由微波电真空器件，如反射速调管、磁控管、行波管等构成，产生的微波噪声大、稳定性较差，已经很难满足如今的应用需求。微波光子学作为一门新兴学科，为产生高性能的微波信号提供了新的解决方案，如光外差法[4-7]、外调制法[8-9]、直接调制法[10-11]、光电振荡器(OEO)[12]等。在上述方法中，OEO的特点是可以产生高频、超低相位噪声[13]的微波信号。OEO一般由光源、电光调制器、光电探测器(PD)、电滤波器、电放大器(EA)和较长的传输光纤组成。为了获得高Q值和低相位噪声的微波信号，通常在环路中加入较长的低损耗光纤，并通过在振荡环路中加入带通微波滤波器来实现对输出信号频率的选择。OEO因其产生的微波信号质量良好，引起了国内外研究人员的广泛关注。

利用OEO产生性能更加优异的微波信号一直是研究人员探索的重点。1994年，Yao等[12]搭建了1个环长为9 m的OEO，通过在环路中加入微波滤波器得到了9.22 GHz的微波信号。由于环路较短，输出信号相位噪声较大，但该实验为进一步研究低相位噪声的OEO奠定了基础。2016年，Xie等[14]使用1个双平行马赫-曾德尔调制器和2个电滤波器构建双频OEO，双频输出的相位噪声优于－120 dBc/Hz@10 kHz。但实验中存在跳频现象，频率稳定性较差，且结构中存在2个电滤波器和3个PD，较为复杂。为了使OEO产生的微波信号频率更为稳定，研究人员做了许多尝试。2002年，Eliyahu等[15]通过对谐振环路中的窄通带微波滤波器进行温度控制，得到了10 GHz稳定振荡的微波信号。其频率偏差从83 kHz/℃提高到1 kHz/℃，短期频率偏差为0.2 kHz，相位噪声为－143 dBc/Hz@10 kHz。2012年，Bui等[16]提出一种控制电光调制器光学偏置点的方法来提高OEO的频率稳定性，OEO的稳定工作时间从2 h提高到8 h。同年，Tseng等[17]使用注入探测信号的方法来监测光纤环路的相位变化，并通过调谐环路中单模光纤的长度来达到频率稳定的目的。2017年，Hosseini等[18]搭建了基于光纤Sagnac干涉仪的OEO，获得了频率为10.833 GHz、相位噪声为－106.6 dBc/Hz@10 kHz的微波信号，连续工作35 h内频率最大偏差为9.21 kHz。上述研究报道中对振荡频率的选择均是通过电滤波器来实现的，并通过对强度调制器、光纤或电滤波器等器件进行有效的控制来达到提高输出信号频率稳定性的目的。上述报道虽然提高了频率的稳定性，但由于结构中包含电滤波器，在一定程度上限制了OEO的可调谐性及可集成度。近年来，科研工作者采用微波光子滤波器(MPF)代替电滤波器，可以简化OEO结构。MPF是在全光域上实现微波信号滤波的方法之一，通过相应的光学器件达到特定频率

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通过、其他频率抑制的目的。MPF具有可调谐性好、抗电磁干扰强、低损耗等优点。2017年，Peng[19]设计了一种基于布里渊损耗谱滤波的OEO，通过MPF实现选频，获得了10.69 GHz的信号输出，其最大频率漂移和最大功率抖动分别为5.7 kHz和1.4 dB。该研究虽然提高了输出信号的频率稳定性，但由于结构中使用了低通滤波器，振荡器结构并没有得到简化。

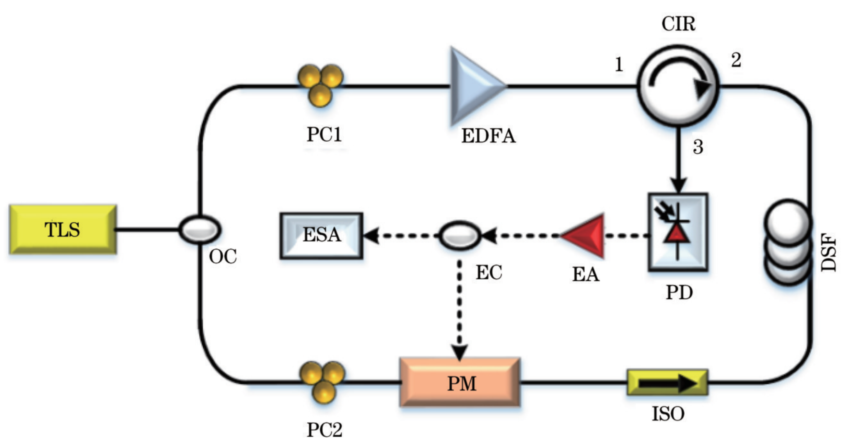
本文提出一种基于受激布里渊散射(SBS)的可调谐稳定OEO。实验中光载波和泵浦光来自同一可调谐激光器，利用泵浦光在较长的色散位移光纤(DSF)中发生SBS效应产生的布里渊增益谱和损耗谱打破相位调制信号的边带幅度平衡，从而达到滤波的效果。使用DSF减弱色散对相位调制信号边带相位的影响。通过改变可调谐激光器的输出波长，可以实现输出微波信号频率的可调谐。实验获得了频率从10.13～10.65 GHz可调的微波信号，调谐范围为520 MHz。在10.48 GHz处测得的相位噪声为−94 dBc/Hz@10 kHz，20 min内最大功率抖动为1.15 dB，在扫描分辨率为1 MHz的条件下测得的输出信号频率无波动。与使用两台激光器分别作为光载波和泵浦光的OEO进行的对比实验结果表明，单光源OEO产生的微波信号频率和功率稳定性更高。所设计的OEO具有结构简单、频率可调谐、稳定性高等优点。

2 实验结构与原理

实验室搭建了如图1所示的OEO结构。1.5 μm的可调谐激光器(Tektronix，OM2210)通过一个20:80的光耦合器(OC)后分为上下两路。下支路作为光载波经过偏振控制器(PC2)后输入相位调制器(PM，KG-PM-15-20-G-PP-FA)，随后通过隔离器(ISO)进入长为3 km的DSF。上支路作为泵浦光经掺铒光纤放大器(EDFA，AEDFA-23-B-FA)放大后，通过光环形器进入DSF。使用DSF是为了确保相位调制到幅度调制的改变是由SBS引起的，而不是由光纤色散造成的。环形器3端口输出的光信号进入PD拍频探测。PD的白噪声经过EA放大后由50:50的电耦合器分为两路，一路连接频谱分析仪(ESA，N9030A)进行频谱分析，另一路反馈至PM形成闭环。在放大后的噪声驱动下，经PM输出的光载波光谱上产生调制边带，如图2(a)所示，其中，λ_c表示光载波波长。功率足够大的泵浦光通过DSF时会发生SBS效应，如图2(b)所示，其中，λ_p表示泵浦光波长，泵浦光的两侧产生频率间隔为布里渊频移ν_B的布里渊增益谱和布里渊损耗谱。布里渊增益谱会放大落入其中的相位调制边带，布里渊损耗谱会衰减落入其中的相位调制边带，如图2(c)所示。经PD探测后，被放大或衰减的边带将与光载波拍频，得到频率大小为ν_B的微波信号。该微波信号反过来驱动PM，使相位调制光载波在相同位置产生强度更大的边带。通过这种正反馈作用，最终得到稳定振荡的微波信号。ν_B可表示为

$$\nu_B=\frac{2n_pV_A}{\lambda_p}, \tag{1}$$

式中：n_p为光纤在λ_p波长处的折射率；V_A为声波在光纤中的传播速度。由式(1)可以看出，随着λ_p的增加，ν_B将减小。因此，通过调节可调谐激光器输出波长，可以使输出微波信号的频率发生改变。



TLS: tunable laser source; OC: optical coupler; PC: polarization controller; PM: phase modulator; ISO: isolator; DSF: dispersion-shifted fiber; EDFA: erbium-doped optical fiber amplifier; CIR: circulator; PD: photodetector; EA: electronic amplifier; EC: electric coupler; ESA: electronic spectrum analyzer

图1 OEO结构

Fig. 1 OEO structure

3 微波光子滤波器频率响应仿真与实验分析

3.1 微波光子滤波器频率响应仿真分析

为了研究MPF的滤波特性，首先采取基于式(2)的数值仿真对其进行模拟分析。单波长泵浦时MPF的频率响应函数[20]为

$$\left|H(f_m)\right|=1+G(f_m)^2A(f_m)^2-2G(f_m)A(f_m)\cos\left[\phi_g(f_m)+\phi_a(f_m)\right], \tag{2}$$

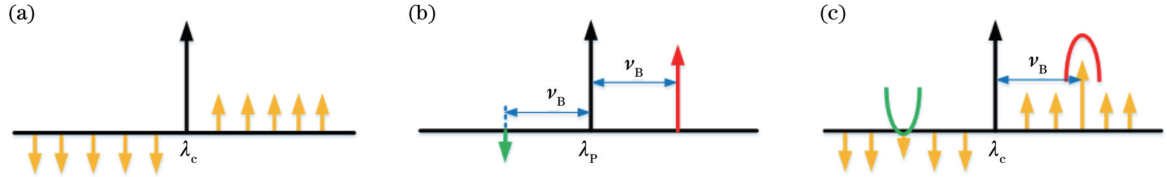


图 2　MPF 滤波原理图。(a)相位调制信号的光谱；(b)泵浦光的光谱；(c) SBS 放大及损耗相位调制边带的光谱

Fig. 2　Schematic diagrams of the MPF filter. (a) The spectrum of phase modulated signal; (b) the spectrum of pump light; (c) the spectrum of phase modulated signal that is amplified and lost by SBS

式中：f_m 为微波信号频率；G、A 分别表示 SBS 的增益和损耗；ϕ_g、ϕ_α 分别表示 SBS 的增益和损耗使相应的相位调制边带发生的非线性相移，它们的表达式如下：

$$G(f_m)=\exp\left[\frac{g_B IL}{2}\frac{(\Delta\nu_B/2)^2}{(f_p-\nu_B-f_c-f_m)^2+(\Delta\nu_B/2)^2}\right],\tag{3}$$

$$A(f_m)=\exp\left[-\frac{g_B IL}{2}\frac{(\Delta\nu_B/2)^2}{(f_p+\nu_B-f_c-f_m)^2+(\Delta\nu_B/2)^2}\right],\tag{4}$$

$$\phi_g(f_m)=\frac{g_B IL}{4}\frac{\Delta\nu_B(f_p-\nu_B-f_c-f_m)}{(f_p-\nu_B-f_c-f_m)^2+(\Delta\nu_B/2)^2},\tag{5}$$

$$\phi_\alpha(f_m)=-\frac{g_B IL}{4}\frac{\Delta\nu_B(f_p+\nu_B-f_c-f_m)}{(f_p+\nu_B-f_c-f_m)^2+(\Delta\nu_B/2)^2},\tag{6}$$

式中：g_B 为布里渊峰值增益系数；I 为泵浦光强度，$I=P/A_{eff}$，P 为泵浦光功率，A_{eff} 为光纤有效模场面积；L 为光纤长度；$\Delta\nu_B$ 为布里渊增益线宽；f_p、f_c 分别为泵浦光和光载波频率。利用式(1)～(6)仿真 MPF 的频率响应，由于泵浦光和光载波来自同一激光器，因此 $f_p=f_c$，仿真中的参数设置如表 1 所示，MPF 频率响应仿真结果如图 3 所示。

表 1　MPF 频谱响应的仿真参数

Table 1　Simulation parameters of MPF spectrum response

Name	Symbol	Value	Unit
Fiber length	L	3000	m
Gain bandwidth of SBS	$\Delta\nu_B$	40	MHz
Line center Brillouin gain coefficient	g_B	2×10^{-11}	m/W
Frequency of pump laser	f_p	186567；190144；193174；196463	GHz
Frequency of optical carrier	f_c	186567；190144；193174；196463	GHz
Pump light intensity	I	7×10^7	W/m^2

由图 3 可以看到，MPF 频率响应只有一个通带。这是因为光载波和泵浦光具有相同频率，泵浦光产生的布里渊增益谱和布里渊损耗谱使相位调制信号的边带对称位置被增益或损耗，被增益或损耗的边带再与光载波拍频，MPF 只能产生一个滤波通带。改变泵浦光波长，可以实现 MPF 中心频率的调谐。

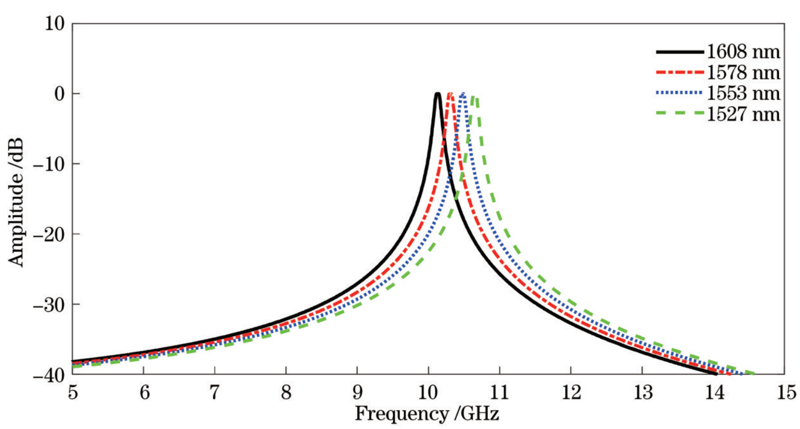


图 3　MPF 频率响应仿真结果

Fig. 3　Simulation result of MPF frequency response

3.2　微波光子滤波器频率响应实验分析

在实验室搭建了如图 4 所示实验结构测量 MPF 的频率响应。与 OEO 不同的是，MPF 结构中由矢量网络分析仪(VNA，N5230A)向 PM 加载扫频信号，同

时PD探测到的信号进入VNA分析。图5为MPF频率响应通带，通过调节激光器波长可使ν_B发生变化，实现MPF中心频率的调谐。VNA测量结果表明，MPF频率响应的3 dB带宽约为50 MHz，MPF可以实现窄带滤波。值得注意的是，由于结构中使用DSF，因此减弱了色散对MPF频谱响应通带的影响。由图3、5可知，仿真与实验结果基本一致，基于SBS的MPF可以实现单通带滤波，因此可以代替电滤波器在OEO中实现选频。

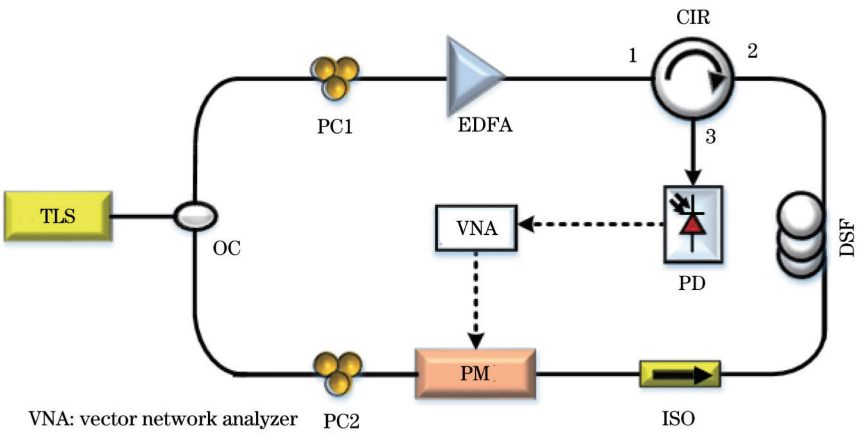


图4 MPF结构

Fig. 4 MPF structure

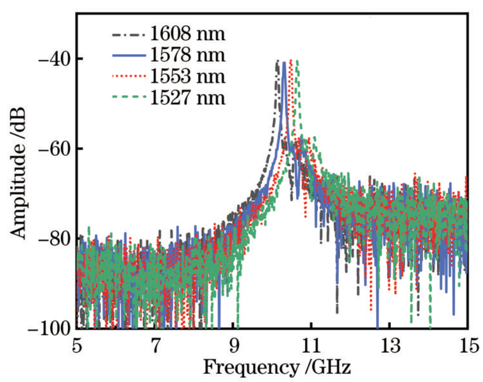


图5 MPF频率响应实验结果

Fig. 5 Experimental results of MPF frequency response

4 实验结果与讨论

4.1 单光源OEO输出微波信号及其稳定性分析

设定可调谐激光器的输出波长为1553 nm时，OEO输出的微波信号频率为10.48 GHz，如图6(a)所示。OEO产生频率为布里渊频移值的微波信号，说明基于SBS的MPF起到了很好的滤波效果。通过ESA测得的微波信号的相位噪声为−94 dBc/Hz@10 kHz。将可调谐激光器的输出波长从1608 nm调谐至1527 nm，输出微波信号的频率相应地可以从10.13 GHz调谐至10.65 GHz，调谐范围为520 MHz，结果如图6(b)所示。为了分析输出信号的稳定性，在20 min内每隔2 min对OEO输出微波信号的频率和功率进行一次记录。在扫描分辨率为1 MHz的情况下，频率为10.48 GHz的微波信号在20 min内频率无波动，如图7(a)所示。图7(b)为输出微波信号的强度变化，20 min内的最大变化量为1.15 dB。由于泵浦光和光载波来自于同一激光器，且结构中并未使用其他调制器对泵浦光波长进行调制，没有引入偏压调节器件，因此获得微波信号的频率及强度较为稳定。

文献[15-18]介绍的OEO均使用电滤波器实现振荡频率的选择，因此OEO输出微波信号频率单一，且文献[17]中OEO输出微波信号频率为69.3 MHz。与文献[15-18]相比，本研究采用SBS效应代替电滤波器滤波简化了装置结构，提高了装置可集成度，所提OEO不仅能够输出高频微波信号，而且微波信号的频率具有一定范围的可调谐性。与文献[19]相比，所设计的OEO泵浦光和光载波由同一光源提供，且环路中没有低通滤波器，简化了OEO结构，输出微波信号强度的稳定性提升约0.45 dB。

4.2 使用两个独立光源的OEO输出微波信号及其稳定性分析

为了对比光载波和泵浦光来自同一激光器和不同激光器时对输出微波信号稳定性的影响，将图1结构中的光载波和泵浦光改为由两台独立的激光器产生。在其他结构参数不变的情况下，采用相同的方法对输出微波信号的频率和强度稳定性进行测量。如图8(a)所示，泵浦光波长λ_{c2}为1553.07 nm，光载波波长λ_{p2}为1553.25 nm，由泵浦光产生的斯托克斯光λ_s波长为1553.16 nm。产生的微波信号频率为11 GHz，如图8(b)所示。微波信号的频率和强度随时间的变化情况如图9所示。从图9(a)可以看出，输出微波信号的频率波动为82 MHz。从图9(b)可以看出，输出微波信号的强度波动为1.69 dB。因为两台激光器的输出波长会有不同的漂移情况，所以产生的微波信号频率和

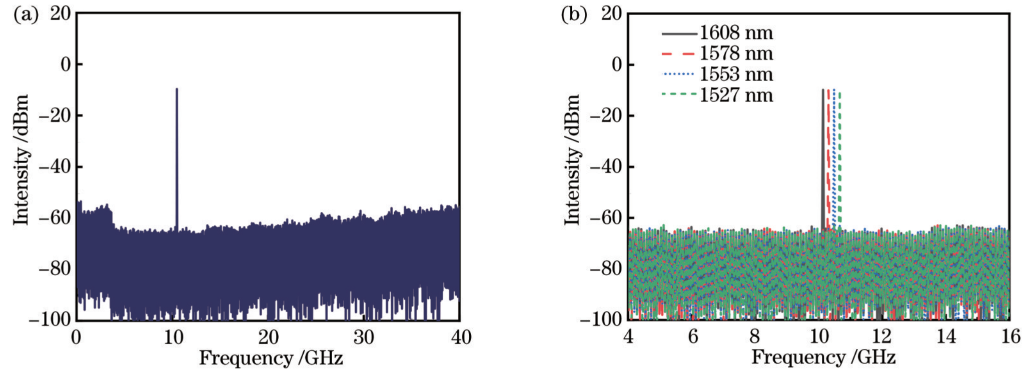


图 6 单光源 OEO 输出微波信号频谱。(a)激光器波长为 1553 nm 时的输出频谱;(b)激光器波长为 1608 nm、1578 nm、1553 nm、1527 nm 时的输出频谱

Fig. 6 The output microwave signal spectrums of single source OEO. (a) The output spectrum when the laser wavelength is 1553 nm; (b) the output spectrums when the laser wavelength is 1608 nm, 1578 nm, 1553 nm, and 1527 nm

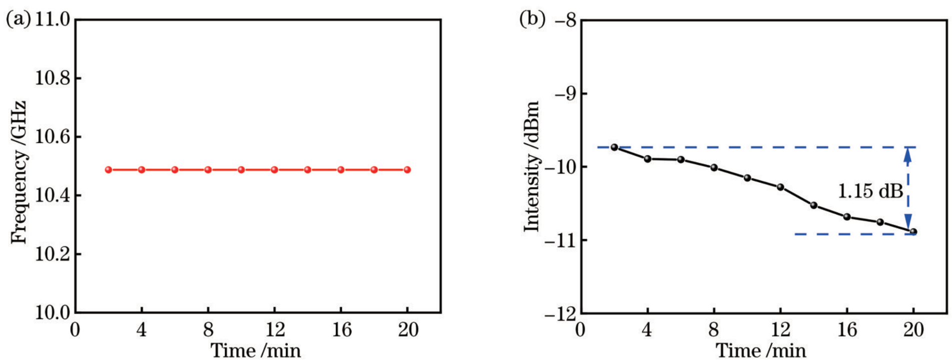


图 7 单光源 OEO 输出微波信号频率及强度稳定性。(a)微波信号的频率稳定性;(b)微波信号的强度稳定性

Fig. 7 Stability of microwave signal frequency and intensity output by OEO of single light source. (a) Frequency stability of microwave signal; (b) intensity stability of microwave signal

强度波动较大,稳定性较差。相较于使用两台独立光源分别提供光载波和泵浦光的 OEO,单光源 OEO 输出微波信号强度稳定性提高了 0.54 dB,在 1 MHz 测量分辨率下频率无波动。

由此可见,光载波和泵浦光源于一台可调谐激光器的 OEO 不仅简化了实验结构,产生的微波信号频率和功率稳定性也都优于泵浦光和光载波使用不同光源的 OEO。

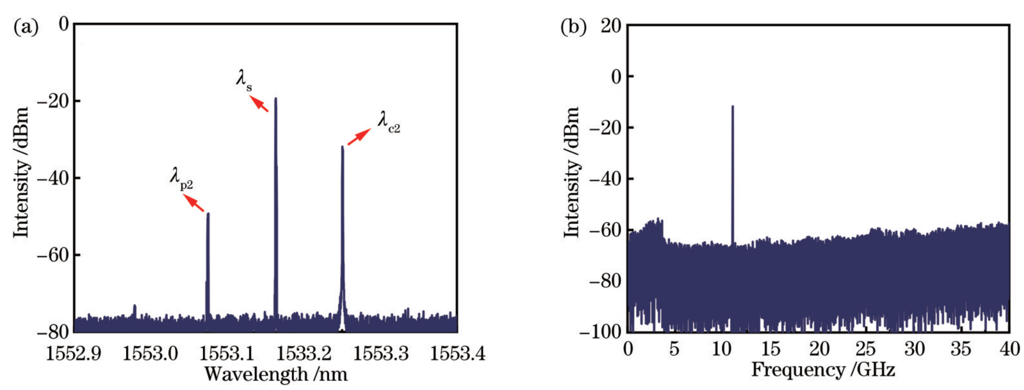


图 8 双光源 OEO。(a)得到的光谱;(b)输出微波信号的频谱

Fig. 8 The OEO with dual light sources. (a) The resulting spectrum; (b) spectrum of the output microwave signal

5 结 论

搭建了基于 SBS 的可调谐 OEO,该 OEO 同时具备可调谐、高频、稳定性高及相位噪声低等的优势。通过改变可调谐激光器的输出波长,实现了输出微波信号频率从 10.13~10.65 GHz 的调谐,调谐范围为 520 MHz。在 10.48 GHz 处测得其相位噪声为 −94 dBc/Hz@10 kHz,20 min 内频率无漂移,功率最

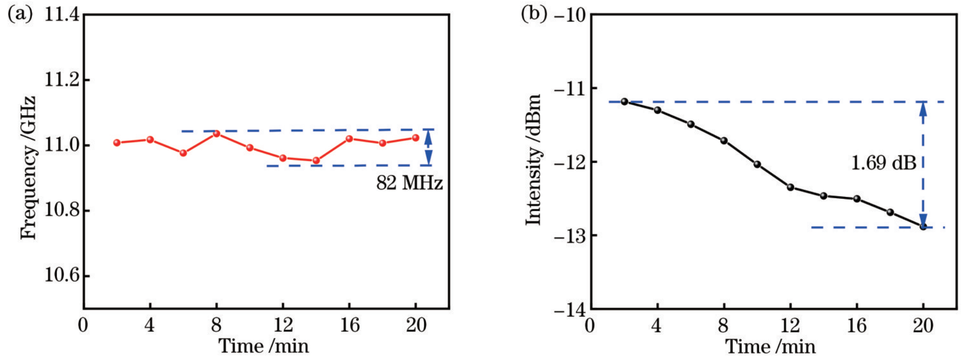


图 9 双光源 OEO 输出微波信号频率及强度稳定性。(a)微波信号的频率稳定性；(b)微波信号的强度稳定性

Fig. 9 Stability of microwave signal frequency and intensity output by OEO of dual light sources. (a) Frequency stability of microwave signal; (b) intensity stability of microwave signal

大漂移量为 1.15 dB。与搭建的双光源 OEO 对比实验结果表明，单光源 OEO 不仅结构简单，输出的微波信号还具有更高的稳定性。该方法是获得高频、低相位噪声、高稳定性的微波信号的较好选择。

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Tunable Stabilized Optoelectronic Oscillator Based on Stimulated Brillouin Scattering

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Abstract

Objective A tunable stabilized optoelectronic oscillator (OEO) based on stimulated Brillouin scattering (SBS) is proposed to solve the low stability problem of microwave signals output by the OEO. An OEO is affected by the characteristics of devices in the structure and the external environment, and the frequency and intensity of its output microwave signals have a certain degree of fluctuations, which influences its subsequent application. Therefore, it is important to improve the stability of microwave signals output by OEOs for improvement in OEO performance. For the OEO based on electric filters to achieve oscillation frequency selection, researchers have improved the frequency stability of output signals by effectively controlling devices such as intensity modulators and optical fibers or electric filters. However, the inclusion of an electrical filter in the structure limits the tunability and integrability of the OEO to some degree. Researchers have introduced the SBS effect into the OEO loop instead of the electrical filter to achieve the oscillation frequency selection so that the tunable range of OEO can be increased. However, the OEO structure usually confronts the problems of laser wavelength drift and DC bias drift, which affect the stability of the microwave signal output by OEO. Therefore, this study proposes a simple-structured OEO that can output a more stable microwave signal and achieve more integrated devices.

Methods A single light source is used to provide an optical carrier and pump light, and the phase modulator (PM) is used to modulate the phase of the optical carrier. It is worth mentioning that the RF signal initially loaded onto the PM comes from the white noise at the photodetector (PD), which is amplified by an electrical amplifier (EA) and fed back to the RF port of the PM to realize the phase modulation of the optical carrier. The Brillouin gain spectrum and Brillouin loss spectrum generated by the SBS effect of pump light in the dispersion-shifted fiber (DSF) break the amplitude balance of the phase modulation sidebands of the optical carrier, and the light wave is photoelectrically converted by the PD to obtain a microwave signal. Then, the microwave signal is fed back to the PM, and through continuous positive feedback, the OEO finally outputs a stable oscillating microwave signal. For higher stability of microwave signals, a tunable stabilized OEO based on SBS is designed. the SBS effect is used instead of an electrical filter to achieve frequency selection, and a single light source is used to provide the optical carrier and pump light, which simplifies the device structure. No other bias regulating devices are introduced into the structure to avoid the effect of DC bias drift, which makes the microwave signal output by the OEO more stable. The use of DSF as the SBS effect medium in the structure reduces the influence of the phase changes in the phase modulation sidebands of the optical carrier caused by the fiber dispersion effect.

Results and Discussions A tunable OEO based on SBS is designed to raise the stability of its output microwave signal. The frequency of microwave signal output by the OEO with a laser wavelength of 1553 nm is 10. 48 GHz (Fig. 6(a)), and the measured phase noise is −94 dBc/Hz@10 kHz. Through adjustment to the laser output wavelength, the OEO outputs a microwave signal tunable in the range of 10. 13 GHz to 10. 65 GHz (Fig. 6(b)), i. e. , a tuning range of 520 MHz. At the resolution of 1 MHz, the frequency and intensity stability of the microwave signal output by the OEO is measured within 20 min. In addition, there is no drift in frequency (Fig. 7(a)), and the intensity fluctuation is 1. 15 dB (Fig. 7(b)). Under the same conditions, when the optical carrier and pump light are provided by two independent light sources, the microwave signal output by the OEO has a frequency fluctuation of 82 MHz (Fig. 9(a)) and an intensity fluctuation of 1. 69 dB (Fig. 9(b)). The experimental results show that compared with the OEO that uses two independent light sources to provide the optical carrier and pump light, the single-source OEO has a simple structure, and the intensity stability of its output microwave signal is improved by 0. 54 dB, with its frequency measured without fluctuations at 1 MHz resolution.

Conclusions In this paper, a tunable OEO based on SBS is proposed, which has the advantages of high frequency, high stability, low phase noise, and tunable output frequency. The output microwave signal frequency is tuned from 10. 13 GHz to 10. 65 GHz, i. e. , a tuning range of 520 MHz, by changing the output wavelength of the tunable laser. The phase noise is measured at 10. 48 GHz to be −94 dBc/Hz@10 kHz, and the output microwave signal reports no frequency drift in 20 min and a maximum power drift of 1. 15 dB. The experimental results show that compared with the dual-source OEO, the single-source OEO has a simple structure and can output a more stable microwave signal. It is a better choice for obtaining a microwave signal with high frequency, low phase noise, and high stability.

Key words optical devices; optoelectronics; microwave photonics; stimulated Brillouin scattering; optoelectronic oscillator; frequency tunable