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频率间隔可切换多波长随机光纤激光器

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摘　要：提出一种基于腔损耗调控的频率间隔可切换多波长布里渊-拉曼随机光纤激光器。该激光器的一侧具有一个反射率可调的反射环，环内有一个可调衰减器，通过调节可调衰减器的衰减大小，从而改变反射环的反射率，可以切换所产生多波长信道的光信噪比和频率间隔。实验中，当可调衰减器衰减较小时（−2 dB），该随机激光器实际为半开腔结构，获得了带宽39 nm（1 532～1 571 nm）、单倍布里渊频移间隔（10.48 GHz）的多波长信道，此时光信噪比为17.2 dB。当可调衰减器衰减较大时（−30 dB），该随机激光器等效为双开腔结构，获得了带宽39.5 nm（1 532～1 571.5 nm）、双倍布里渊频移间隔（20.96 GHz）的多波长信道，此时光信噪比为25.2 dB。该结构相比其他频率间隔可切换多波长光纤激光器具有结构简单、信道带宽更宽等优点。

关键词：随机光纤激光器；多波长；受激布里渊散射；受激拉曼散射；瑞利散射
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0 引言

自2010年分布反馈式随机光纤激光器[1]的结构被提出以来，随机分布反馈的光纤激光器因具有高功率[2-3]、多波长[4]、可调谐[5-7]和窄线宽[8]等突出优势，在高功率[9]、宽谱发射[10-11]、低相干性[12]等多类型新光源探索方面具有广阔的发展前景。不同于传统光纤激光器具有确切的反馈谐振腔镜，随机光纤激光器没有传统意义上界限明确的谐振腔结构，而是依靠光纤内的随机散射来进行光反馈。根据反馈类型，随机光纤激光器可分为基于瑞利散射的分布反馈随机光纤激光器[1]、填充型随机光纤激光器[12-13]和基于随机光栅的随机光纤激光器[14-15]。然而，填充型随机光纤激光器因需要特种空芯光纤、合适的增益及散射介质填充，具有结构复杂、腔损耗大、输出激光效率低、实用化程度低等缺点。另一种基于随机光栅的随机光纤激光器由于输出光谱具有强模式竞争导致输出功率、效率低且光谱不稳定。为了克服上述随机光纤激光器带来的问题，基于瑞利散射分布反馈的随机光纤激光器因具有高平稳的窄带连续无模谱输出、非线性功率展宽、简单结构、体积小且成本低等突出优势，被国内外学者广泛研究。

近年来，关于随机光纤激光器的多项研究报道中，广泛地应用了受激布里渊散射（Stimulated Brillouin Scattering，SBS）与受激拉曼散射（Stimulated Raman Scattering，SRS）等非线性效应，并利用基于瑞利散射（Rayleigh Scattering，RS）所形成的随机分布式反馈以实现多波长级联输出。SONEE S R等[16]提出了一种由11 km长的色散补偿光纤和25 km长大模场面积光纤的组合提供增益的多波长布里渊-拉曼随机光纤激光器，一端输出端增加反射镜将偶数阶斯托克斯线和泵浦光反射回空腔，实现了光信噪比均匀且信道间隔约为10 GHz的多波长信道输出。WU H等[17]通过在多波长布里渊-拉曼随机光纤激光器泵浦侧增加一个高反射率的反射环镜，克服了相邻信道之间功率水平和线宽的差异，获得了平均信噪比为13.5 dB的210阶信

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道间隔约为10 GHz的多波长信道。虽然多波长布里渊-拉曼随机光纤激光器通常在信道之间有10 GHz的间距,但激光腔也可以通过配置不同结构来获得不同的波长间隔。MAMDOOHI G等[18]提出了一种全开腔布里渊—拉曼多波长随机光纤激光器结构,以双氧化铋掺铒光纤(Bi-EDF)作为增益介质,在11 km色散补偿光纤内实现了平均信噪比为26 dB的195阶信道间隔约为20 GHz的多波长信道输出。许磊等[19]研究发现,在全开腔结构上加入一段4 m的掺铒光纤,可以优化双倍布里渊频移间隔的多波长信道的边模抑制比,即从14 dB提高至20 dB。MEI J等[20]进一步提高全开腔布里渊—拉曼多波长随机光纤激光器的性能,将掺铒光纤放大器与单模光纤结合在一侧,进行随机激光再生,实现了对光谱平整度和边模抑制比的改善。

上述多波长布里渊-拉曼随机光纤激光器中,瑞利散射(RS)是诱导级联受激布里渊散射(SBS)的关键,多波长斯托克斯线(Brillouin Stocks Line, BSL)的产生是SBS、RS、SRS在高拉曼泵浦(Raman Bump, RP)功率下结合的结果。然而,上述多波长激光器的结构是刚性的,输出光谱中相邻BSLs只能有单倍布里渊频移间隔或双倍布里渊频移间隔。因此一个具有可调频率间隔的单一多波长布里渊-拉曼随机光纤激光器值得深入探索。

已有研究表明半开腔布里渊-拉曼随机光纤激光腔可以产生信道间隔约为单倍布里渊频移间距的多波长随机激光[16-17],全开腔结构可以产生信道间隔约为双倍布里渊频移间距的多波长随机激光[18-20]。本文提出一种频率间隔可切换的多波长布里渊-拉曼随机光纤激光器,其频率间隔可切换功能是通过调控半开腔一侧反射环中的可调衰减器的衰减大小,即控制反射光的功率变化实现的。基于此,当可调衰减器衰减较小时(−2 dB),此时大部分的偶数阶斯托克斯光和剩余泵浦光被反射回激光腔中,继续参与级联,该激光器实际为半开腔结构,获得带宽39 nm(1 532 ~1 571 nm)、单倍布里渊频移间隔(10.48 GHz)的多波长信道,此时光信噪比为17.2 dB。当可调谐衰减器衰减较大时(−30 dB),此时偶数阶斯托克斯光从右端输出口输出,不会返回到激光腔中,该激光器等效为双开腔结构,获得带宽39.5 nm(1 532 ~1 571.5 nm)、双倍布里渊频移间隔(20.96 GHz)的多波长信道,此时光信噪比为25.2 dB。该结构相比其他频率间隔可切换多波长光纤激光器具有结构简单、信道带宽更宽等优点。

1 激光器结构及工作原理

基于腔损耗调控的频率间隔可切换多波长布里渊-拉曼随机光纤激光器的结构如图1。该随机光纤激光器结构由一个拉曼光纤放大器以及两个个反射环组成,其中放大器由一个波分复用器(WDM)、拉曼泵浦RP(OS8147-850-1455,工作波长为1 455 nm)和色散补偿光纤(DCF)组成。长度7 km的DCF(DCF与SMF在1 550 nm处熔接后的总插入损耗约为5.6 dB)作为布里渊和拉曼混合非线性增益介质,与单模光纤(SMF)或非零色散光纤(NZ-DSF)相比,其有效面积更小,可以为多波长布里渊-拉曼光纤激光器提供更高的增益。实验结构中,理论计算得到DCF的布里渊频移为11.28 GHz,除了利用受激布里渊散射效应产生级联斯托克斯线外,还充当随机分布反射镜,即基于后向弱瑞利散射形成分布式激光反射。 反射环1由环形器(Cir3)端口3与端口1相连构成,使得从DCF出来的剩余没被吸收的RP能够返回腔内,继续对布里渊泵浦(BP)和BSL进行拉曼放大,提高RP的利用效率。反射环2由环形器(Cir2)端口3与端口1间连接一个可调衰减器构成,通过控制可调衰减器的衰减大小,使激光器结构在半开腔与全开腔之间切换,从而调控所产生多波长信道的频率间隔和光信噪比。在环形器(Cir1)端口3连接一个分辨率0.02 nm的光谱分析仪

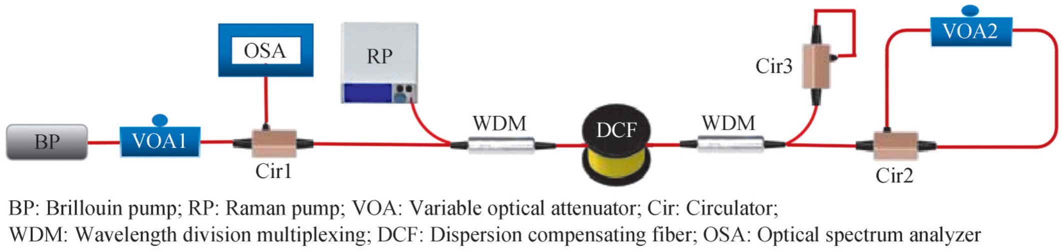


图1 基于腔损耗调控的频率间隔可切换多波长布里渊-拉曼随机光纤激光器结构

Fig.1 Structure of frequency interval switchable multi-wavelength Brillouin-Raman random fiber laser based on cavity loss regulation

(OSA,AQ6370D)来测量激光器的性能以及多波长输出的光谱。

该激光器工作原理:采用半导体可调谐激光源(AQ2200-136,线宽为200 kHz)作为BP,波长调谐范围为970 ~1 680 nm,通过可调谐衰减器调整注入激光腔的信号功率,功率调谐范围为−60 ~6 dBm。BP信号通过环形器(Cir1)端口1注入激光腔,经过1 455/1 550 nm的波分复用器(WDM)与1 455 nm RP信号结合。RP在DCF中产生分布式拉曼效应,对BP进行拉曼放大。当BP信号功率达到受激布里渊散射阈值时,将产生反向传播的一阶布里渊斯托克斯线(BSL)。类似地,低阶BSL将作为高阶BSL的泵浦源产生更多的高阶BSL,这样的级联过程一直持续到某一阶的放大BSL受到拉曼放大效率的限制,而不能达到下一阶的SBS阈值时停止。另一个波分复用器连接反射环1,用于将剩余没被吸收RP功率反射回腔内,提高RP的利用效率。在该激光器结构中,向右传播的偶数阶BSLs通过反射环2反射回光纤中,与向左传播的奇数阶BSLs结合,共同从环形器(Cir1)端口3处输出,形成单倍布里渊频率间隔的多波长BSLs。因此通过控制反射环中可调谐衰减器衰减大小,可以精确控制进入腔内的反射信号的功率,形成频率间隔可切换、信噪比可调的多波长信道输出。

2 实验结果及讨论

2.1 反射环的表征

图2为反射环2的细节图,它由一个环形器(Cir2)以及一个可调谐衰减器构成。采用光功率计(OPM)测量通过可调谐衰减器前的入射功率以及通过衰减器后的出射功率。环形器可以阻止任何不需要的反向反射光,确保收集到的数据具有高的准确性。测量通过环形器(Cir2)端口3输出的偶数阶斯托克斯线光功率记为入射光功率,再测量继续经过可调谐衰减器后的光功率记为输出功率,通过比较两处功率损失,可以得出反射环中衰减器的衰减大小。

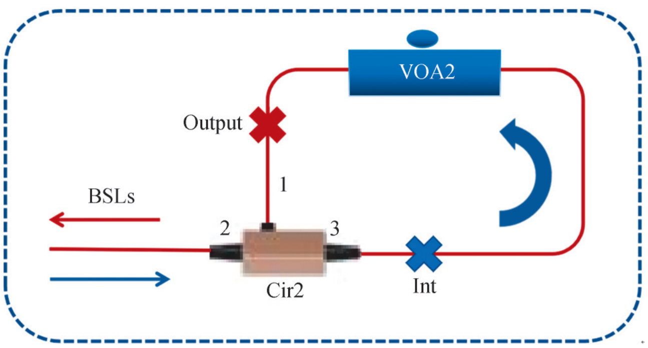


图2 反射环2细节

Fig.2 Detailed for the reflective ring 2

图3为选取BP波长为1 535 nm,功率为4 dBm,RP功率为29.2 dBm情况下,输出光谱及其相邻斯托克斯线之间峰值功率差(PPD)随反射环2中可调衰减器的衰减大小变化关系图。由图3(b)可知,当衰减0 dB到−3 dB时,向右传播的偶数阶BSLs大部分通过反射环2反射回光纤中,与向左传播的奇数阶BSLs结合并同向传播,激光器产生具有单倍布里渊频移间隔的斯托克斯线,此时输出光谱不平整度小于3 dB,即产生了10.48 GHz频率间隔的BSLs(考虑到理论计算中有效折射率以及声学速度取值为近似值带来的误差,该单倍布里渊频移间隔值与理论值有一些偏差)。继续增加衰减,相邻斯托克斯线之间的峰值功率差增大。当衰减−3 dB到−30 dB时,相邻斯托克斯线频率间隔处于由单倍布里渊频移间距向双倍布里渊频移间距过渡区间,此时相邻斯托克斯线之间峰值功率差处于3 dB至20 dB之间。当衰减−30 dB到−65 dB时,激光器产生具有双倍布里渊频移间隔的斯托克斯线,此时仅有偶数阶斯托克斯的瑞利反射分量与奇数阶BSLs同向传播,相邻斯托克斯线之间的峰值功率>20 dB,即产生20.96 GHz频率间隔的BSLs。可见,通过调节可调衰减器的衰减大小,从而精确控制进入腔内的反射信号的功率,可以使激光器结构在半开腔与全开腔之间切换,形成频率间隔可切换、信噪比可调的多波长信道输出。

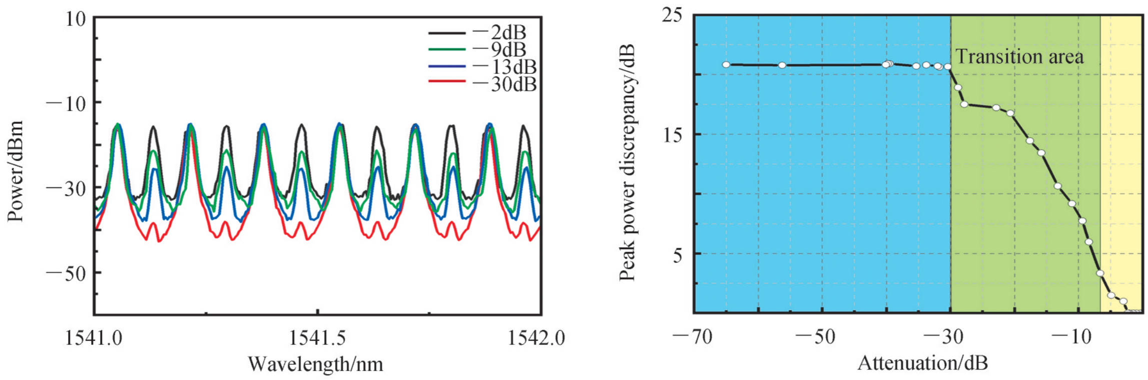


图 3 BSLs之间的PPD随衰减器衰减变化的函数关系

Fig.3 PPD of the BSLs as a function of attenuation of the attenuator

2.2 BP波长及功率对多波长输出的影响

为了说明BP波长(本结构中,输出光谱可以在1 532 nm到1 570 nm之间调谐)对多波长斯托克斯线输出的影响,固定BP功率为4 dBm,RP功率为29.2 dBm,在不同的BP波长下测量多波长布里渊-拉曼随机光纤激光器的输出。图4(a)为在BP波长分别为1 535 nm、1 545 nm、1 555 nm以及1 565 nm的情况下,得到的单倍布里渊频移间隔多波长输出,带宽分别为36 nm、26 nm、16 nm、6 nm。图4(b)为在上述不同BP波长下得到的双倍布里渊频移间隔多波长输出,带宽分别为36.5 nm、26.5 nm、16.5 nm、6.5 nm。结果表明,在该结构下多波长信道的输出带宽随BP波长增大而减小。这是因为在较大波长处的拉曼增益较低,多通道的产生在长波长边缘受到限制。因此,随着BP信号被调谐到更长的波长,斯托克斯线数量的产生会持续下降,带宽降低。

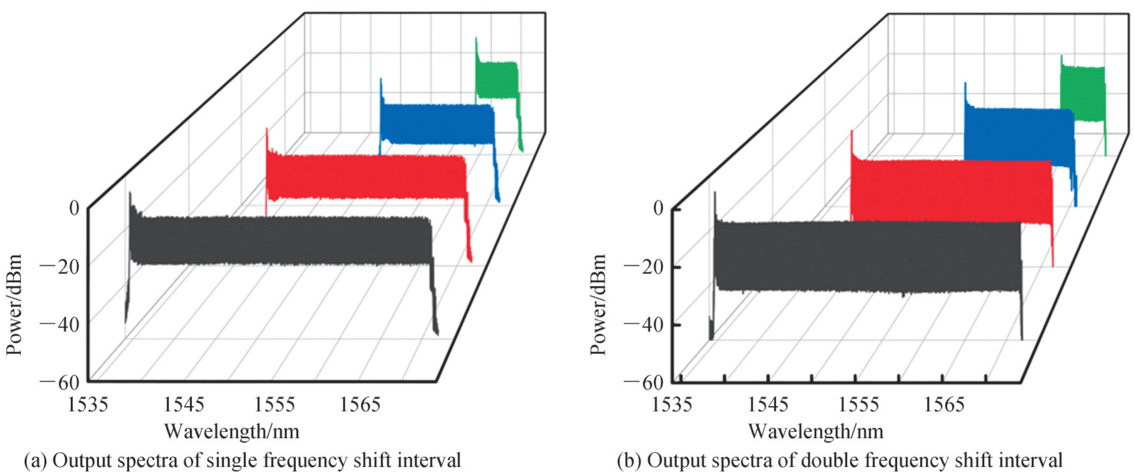
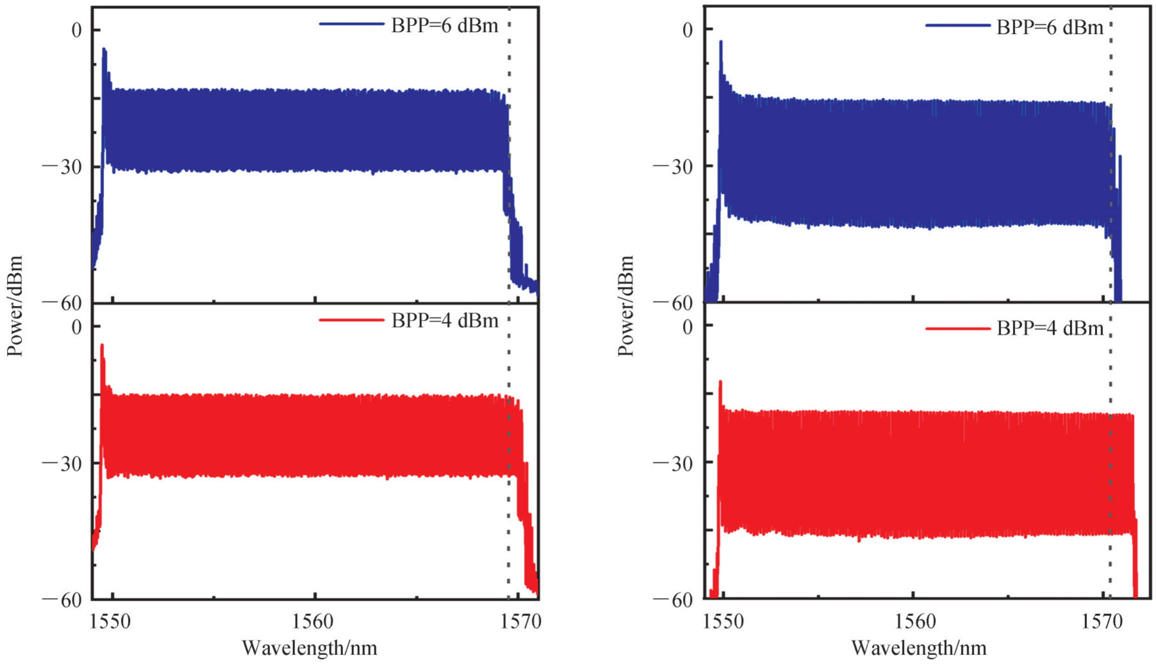


图 4 不同BP波长下得到的两种具有不同布里渊频移间隔的多波长输出光谱

Fig.4 Two multi-wavelength output spectra of different Brillouin frequency shift intervals at different BP wavelengths

如图5所示,进一步讨论BP功率对多波长输出的影响,固定BP波长为1 550 nm,RP功率为29.2 dBm,将1 550 nm BP功率从4 dBm提高到6 dBm,此时单倍频率间隔的多波长输出光谱带宽由20.2 nm减小至19.5 nm,双倍频率间隔的多波长输出光谱带宽由21.6 nm减小至20.6 nm。这是由于在较高BP功率值下,光强增大,此时粒子受激辐射几率下降导致增益趋于饱和(即此时发生了增益饱和),从而阻止了高阶斯托克斯线的进一步放大。因此,多波长输出带宽随着BP功率的增加而减少。若进一步降低BP功率至4 dBm以下,斯托克斯线对自激发模式抑制作用会减小,光谱的稳定性会变差且调谐范围也将大大降低。 因此在该激光结构中,选取BP波长为1 532 nm,功率为4 dBm时,多波长输出在尽可能大的波长范围内输出更多的斯托克斯线。



(a) Output spectra of single frequency shift interval
(b) Output spectra of double frequency shift interval

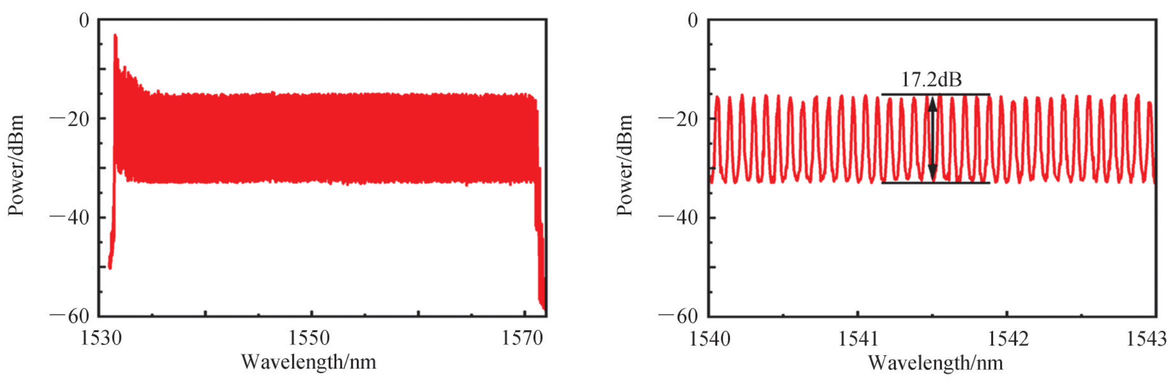
图5 不同BP功率下得到的两种具有不同布里渊频移间隔的多波长输出光谱

Fig.5 Two multi-wavelength output spectra of different Brillouin frequency shift intervals at different BP power

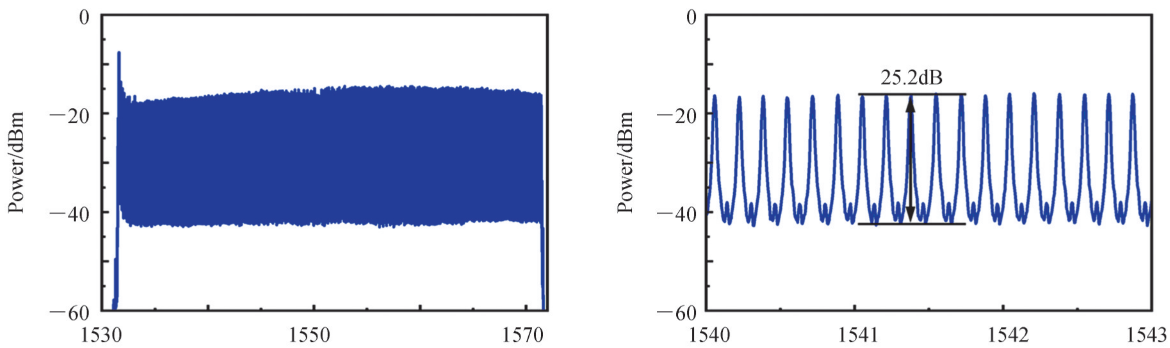
2.3 最佳结果

在本结构中,考虑到产生的斯托克斯线数量与RP功率成正比,且在29.2 dBm处未达到饱和,因此RP选取最高功率29.2 dBm。图6为在最佳泵浦条件下的多波长输出光谱,此时BP波长为1 532 nm,功率为4 dBm,RP功率为29.2 dBm。

如图6,在最佳泵浦条件下,通过调控可调谐衰减器的衰减大小,实现了多波长斯托克斯线输出间隔单双倍布里渊频移切换。当可调衰减器衰减-2 dB时,该激光器实际为半开腔结构,此时大部分偶数阶斯托克斯线被反射环2反射回激光腔中,与奇数阶斯托克斯线汇合同向传输,一起通过环形器(Cir1)端口3被检测,最终获得带宽39 nm(1 532 ~1 571 nm)、频率间隔为10.48 GHz的多波长光谱,此时光信噪比为17.2 dB。当可调衰减器衰减－30 dB时,该激光器等效为全开腔结构,此时大部分偶数阶斯托克斯线通过环形器(Cir2)端口3输出,不返回到腔中,仅有偶数阶斯托克斯瑞利散射分量与奇数阶斯托克斯线同向传输被检测,最终获得带宽39.5 nm(1 532 ~1 571.5 nm)、频率间隔约为20.96 GHz的多波长光谱,此时光信噪比为25.2 dB。该结构相比其他频率间隔可切换多波长光纤激光器具有结构简单、信道带宽更宽等优点。



(a) Output spectra of single frequency shift interval
(b) The detail of (a)



(c) Output spectra of double frequency shift interval　　(d) The detail of (c)

图6　最佳泵浦条件下得到的两种具有不同布里渊频移间隔的多波长输出光谱及其细节

Fig.6　Two multi-wavelength output spectra and their details of different Brillouin frequency shift intervals at optimized pumping condition

3　结论

提出了一种基于腔损耗调控的频率间隔可切换多波长布里渊-拉曼随机光纤激光器。该随机光纤激光器基于瑞利散射所形成的随机分布式反馈,结合受激布里渊散射、受激拉曼散射等非线性效应以实现多波长级联输出。通过控制反射环2中的可调衰减器的衰减大小,腔结构在半开腔与全开腔之间切换,实现多波长斯托克斯线信道的频率间隔切换和光信噪比可调。实验结果表明,当可调衰减器衰减−2 dB时,该激光器实际为半开腔结构,可获得带宽39 nm(1 532 ~1 571 nm)、单倍布里渊频移间隔(10.48 GHz)的多波长信道,此时光信噪比为17.2 dB。当可调衰减器衰减−30 dB时,该激光器等效为全开腔结构,可获得带宽39.5 nm(1 532 ~1 571.5 nm)、双倍布里渊频移间隔(20.96 GHz)的多波长信道,此时光信噪比为25.2 dB。该频率间隔可切换、结构简单的多波长随机光纤激光器大大扩展了其在新光源探索领域应用的灵活性。

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Frequency Interval Switchable Multi-wavelength Random Fiber Laser

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Abstract: Because of their outstanding advantages of high power, high efficiency, multi-wavelength, tunable, narrow linewidth, and variable bandwidth, fiber lasers based on random distributed feedback have a broad development prospect in the exploration of new light sources. Random fiber lasers based on Rayleigh scattering distributed feedback are widely studied and discussed by scholars. As a result, they can overcome the disadvantages of traditional distributed feedback random lasers such as a complex structure, large cavity loss, low output laser efficiency, spectral instability, and low practicality. In recent years, several research reports on random fiber lasers have widely applied the combination of Stimulated Brillouin Scattering(SBS), Stimulated Raman Scattering(SRS), and Rayleigh Scattering(RS) to achieve multi-wavelength cascaded output. A single multi-wavelength Brillouin-Raman random fiber laser with tunable frequency spacing is innovative and worthy of further exploration, considering the lack of flexibility and limited applications of multi-wavelength output at a fixed frequency interval. In this paper, the cavity loss is controlled by tuning the attenuator in the reflection ring, which makes the laser cavity structure switch between a semi-open cavity and a full-open cavity. What′s more, the frequency interval of multi-wavelength output can also be switched by this way. Compared to other multi-wavelength fiber lasers with switchable frequency intervals, this structure is more simple and has a wider output bandwidth. In the current laser configuration, the multi-wavelength cascade output is the result of a combination of SBS, RS, and SRS at high Raman Pumping (RP) power. The RP produces a distributed Raman gain in the DCF and then amplifies the BP. When the BP power satisfies the SBS threshold, a back-propagating first-order Brillouin Stokes Light (BSL) is generated. Similarly, the first-order BSL is also amplified by the distributed Raman gain and acts as a new pump source to generate a second-order BSL that propagates backwards with respect to the first-order BSL. Thus, the lower-order BSLs act as a pump source to generate more higher-order BSLs, and such a cascade process will continue until the overall gain is insufficient to offset its losses. The switchable frequency interval of multi-wavelength output is achieved by tuning the attenuator in the reflective ring 2, which can precisely control the power of the reflected signal entering the cavity. When the attenuation is small, the multi-wavelength output has a single-frequency interval, and when the attenuation is large, the multi-wavelength output has a double-frequency interval. The influence of changing the attenuation in reflection ring 2 on the Peak Power Difference (PPD) between adjacent Stokes lines is discussed in the experiment. When the attenuation is small, most of the even-order BSLs propagating to the right are reflected into the fiber through the reflective ring 2, and then combine with the odd-order BSLs propagating to the left. As a result, the laser produces Stokes lines with a single-frequency interval, at which time the spectral flatness is less than 3 dB, satisfying the condition of producing BSLs with a frequency interval of ~10 GHz. Continuing to increase the attenuation, the frequency interval of adjacent Stokes lines is in the transition from ~10 GHz to ~20 GHz, while the PPD is also changing in the range of 3 dB to 20 dB. When the even-order BSLs propagating to the right are almost all attenuated, the laser produces Stokes lines with a double-frequency interval, and only the even-order Rayleigh components propagate together with the odd-order BSLs. Under this circumstance, the PPD is more than 20 dB and almost constant, which satisfies the condition of producing BSLs with a frequency interval of 20 GHz. The influence of BP wavelength and power on the multi-wavelength output is further discussed in the experiment. The best result is obtained under the optimal experimental conditions, at which multi-wavelength outputs with a single-frequency interval (~10 GHz) in wavelength range of 39 nm (1 532 ~1 571 nm) and multi-wavelength output with a double-frequency interval (~20 GHz) in wavelength range of 39.5 nm (1 532 ~1 571.5 nm) are obtained.A frequency interval switchable multi-wavelength Brillouin-Raman random fiber laser based on cavity loss modulation is proposed and demonstrated. The random fiber laser based on the random distributed feedback is formed by RS combined with nonlinear effects such as SBS and SRS to achieve multi-wavelength cascaded output. Further by controlling the attenuation of the tunable attenuator in the reflective ring 2, the cavity structure is switched between a semi-open cavity and a full-open cavity, which makes the frequency interval and optical signal-to-noise ratio of the multi-wavelength output switchable. The experimental results show that when the attenuation is − 2 dB, the multi-wavelength output with a single-frequency interval (10.48 GHz) in a wavelength range of 39 nm (1 532 ~1 571 nm) can be obtained, and the optical signal-to-noise ratio is 17.2 dB at this time. When the attenuation is − 30 dB, the multi-wavelength output with a double-frequency interval (20.96 GHz) in a wavelength range of 39.5 nm (1 532 ~1 571.5 nm) can be obtained, and the optical signal-to-noise ratio is 25.2 dB at this time. Compared to other multi-wavelength fiber lasers with switchable frequency intervals, this structure is simpler and has a wider output bandwidth.

Key words: Radom fiber laser; Multi-wavelength; Stimulated Brillouin scattering; Stimulated Raman scattering; Rayleigh scattering

OCIS Codes: 140.3550; 060.3510; 190.5890

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