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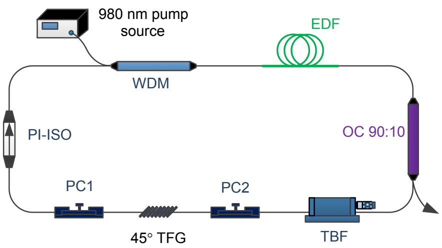

45°倾斜光纤光栅波长可调谐调 Q 光纤激光器

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摘要：本文提出了一种基于 45°倾斜光纤光栅与带通滤波器的连续可调谐全光纤调 Q 掺铒激光器，45°倾斜光纤光栅与其两侧的偏振控制器可以实现非线性偏振旋转效应，调 Q 的产生则是因为非线性偏振旋转效应使环形腔中的激光产生强度依赖损耗从而导致脉冲压缩。在泵浦功率为 655 mW 时，通过调节具有中心波长选择作用的带通滤波器，调 Q 状态下可以实现光谱在 1512 nm~1552 nm 范围内的连续可调，平均输出功率从 0.282 mW 逐渐增加到 4.884 mW，脉冲重复频率从 23.7 kHz 逐渐增加到 119.0 kHz。据我们所知，这是目前为止基于非线性偏振旋转效应与光谱带通滤波器实现的可调谐调 Q 的光纤激光器中连续可调谐波长范围最宽的。

关键词：光纤激光器；调 Q 激光器；光纤光栅；可调谐激光器

中图分类号：O436.3；TN253　　　　**文献标志码：**A

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Wavelength-tunable Q-switched fiber laser based on a 45° tilted fiber grating

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Abstract: A continuously tunable Q-switched all-fiber Er-doped laser based on a 45° tilted fiber grating and tunable bandpass filter is demonstrated. The 45° tilted fiber grating is used to achieve the nonlinear polarization rotation (NPR) along with two polarization controllers (PCs), Q-switching is realized due to the fact that the NPR effect in-

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duced intensity-dependent loss. Under the pump power of 655 mW, the Q-switched optical spectrum can be continuously tuned from 1512 nm to 1552 nm by simply rotating the tunable bandpass filter. During the wavelength tuning process, the average output power increases from 0.282 mW to 4.884 mW while the repetition rate enhances from 27.3 kHz to 119 kHz. To the best of our knowledge, this is the widest continuously tunable range of Q-switched fiber Lasers based on nonlinear polarization rotation effect and spectral bandpass filter.

Keywords: fiber laser; Q-switched laser; fiber grating; tunable laser

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1 引 言

波长可调谐的调 Q 光纤激光器在通信[1]、医疗[2-3]、测距[4]以及激光加工[2, 4-5]等领域[6]都有着重要应用。一般来讲，调 Q 光纤激光器可分为两类——主动调 Q 光纤激光器和被动调 Q 光纤激光器。主动调 Q 光纤激光器需要在激光腔中加入声光或者电光调制器，这增加了激光器的复杂性，同时也提高了激光器的成本[7-8]。相对于主动调 Q 光纤激光器，采用被动调 Q 技术的光纤激光器具有结构紧凑、设计简单和价格低廉等优点。在激光腔中放置半导体可饱和吸收镜[9-10]是应用较早的被动调 Q 的技术，这种方法虽然已经较为成熟，但半导体可饱和吸收镜较窄的工作带宽会限制光谱调谐的范围。利用过渡金属掺杂晶体作为可饱和吸收体同样可以产生调 Q 脉冲，但是这会带来额外的插入损耗[11-12]。在光纤激光器中运用碳纳米管[13-14]作为可饱和吸收体来实现调 Q 脉冲输出可以极大减小腔内的损耗，但是碳纳米管的制备工艺复杂，不易获取。本文提到的非线性偏振旋转技术[15-16]可以等效为人造式可饱和吸收体，相比上述方法，此项技术不仅可以维持光纤激光器的全光纤结构，而且还能通过调节偏振控制器的状态来改变调 Q 脉冲的宽度。本文中的非线性偏振旋转技术是通过 45°倾斜光纤光栅与其两侧的偏振控制器来实现的，45°倾斜光纤光栅具有偏振相关损耗高、鲁棒性强以及成本低廉等优势，目前已经被广泛应用于激光器、成像、光通信、偏振分析等领域[17-21]。这种光纤光栅对不同的偏振光具有不同的衰减特性[17]，它在本文所报道的调 Q 光纤激光器中相当于一个光纤型起偏器[21]，调节其两侧的偏振控制器可以实现调 Q 脉冲的输出。

另一方面，实现调 Q 光纤激光器波长可调谐的方法有：腔外插入光纤布拉格光栅[13]或者衍射体光栅[12, 22-23]、利用环形激光腔内的双折射效应[15]以及使用商用光纤型带通滤波器[24-27]。采用在腔外插入衍射体光栅的方法虽然可以得到较大的调谐范围，但是打破了激光器全光纤的结构。腔外插入光纤布拉格光栅的方案虽然可以实现波长可调谐，却又存在着调谐范围有限的缺点。利用环形光纤激光器腔内的双折射效应可以在调 Q 光纤激光器中实现波长可调谐，但是这种可调谐通常都不是连续的，并且会带来腔长变长、系统复杂的问题。

本文提到的使用商用带通滤波器来实现调 Q 光谱调谐的方法不仅保证了激光器的全光纤结构，而且可以做到输出光谱的中心波长在 1512 nm~1552 nm 范围内连续可调。保证调 Q 状态不变，当泵浦功率从 106 mW 逐渐增加到 661 mW (实验中最大)时，平均输出功率从 0.282 mW 逐渐增加到 4.884 mW，脉冲重复频率从 23.7 kHz 逐渐增加到 119.0 kHz。泵浦功率为 655 mW 时，输出脉冲重复频率为 105 kHz，平均输出功率为 4.45 mW，调 Q 脉冲的信噪比为 39.89 dB。

2 45°倾斜光纤光栅与带通滤波器的特性

45°倾斜光纤光栅具有很强的偏振依赖特性，非偏振光通过此器件之后将变为线性偏振光[17-21]。本实验中所用 45°倾斜光纤光栅的偏振相关损耗(polarization dependent loss, PDL)响应以及插入损耗是由一套商用检测设备(LUNA system)和一台可调谐激光器(Agilent 8164A, 1 pm resolution)一起测量的。测量得到此偏振元件的光谱覆盖范围在 1525 nm~1608 nm 之间。

45°倾斜光纤光栅的主要光谱特性如图 1 所示，可以看到在 1525 nm~1608 nm 光谱范围内平均插入损耗约为 3.7 dB。图 1(a)所示的插入损耗主要是由高阶布拉格反射引起的，这对光栅在实验中的偏振作用没有影响。图 1(b)所示的偏振相关损耗响应是在较宽波长范围(1525 nm~1608 nm)内测量的，这个范围内光栅的偏振相关损耗均大于 12 dB，这表明此光栅是一种有效的宽带宽偏振器件。可以看到，图 1(a)所示插入损

耗特性曲线与图 1(b)所示偏振相关损耗特性曲线都呈现波纹状的抖动。其原因解释如下，当光信号通过 45°倾斜光纤光栅时，垂直偏振光将以辐射模的形式从纤芯向着垂直于光纤轴的方向耦合出去，由于光纤包层有限，部分辐射模将会从包层和空气的边界反射回纤芯与包层的边界，由此形成谐振[28]。在本实验中，上述插入损耗以及偏振相关损耗特性的波动对于激光器的性能没有影响。

实验中所用可调谐带通滤波器的光谱选择特性是通过一个自制的宽带 C 波段光源测量的，结果如图 2 所示。由图 2(a)可知，在 1512 nm~1552 nm 范围内带通滤波器具有良好的波长选择特性，在 1512 nm 附近时滤波器的响应强度有所下降。图 2(b)所示为滤波器在 1548 nm 处的典型光谱特性，3 dB 带宽为 4.22 nm，其余波长处的 3 dB 带宽均与此接近。

3 实验装置

45°倾斜光纤光栅波长可调谐调 Q 光纤激光器的实验结构如图 3 所示，该激光器主要由泵浦源(980 nm pump source)、波分复用器(wavelength division multiplexer, WDM)、掺铒光纤(erbium-doped fiber, EDF)、光纤耦合器(output coupler, OC)、可调谐带通滤波器(tunable bandpass filter, TBF)、45°倾斜光纤光栅(45° tilted fiber grating, 45° TFG)和偏振无关隔离器(polarization-independent isolator, PI-ISO)等器件组成。其中增益介质为长度 0.94 m 的掺铒光纤(EDF)，长度为 9.85 m 的单模光纤(single-mode fiber, SMF)被用来增加光纤的非线性效应及补偿腔内的色散。可调谐带通滤波器具有滤波以及波长选择作用，主要用于实现输出激光光谱的连续可调。45°倾斜光纤光栅(45° TFG)以及其两侧的偏振控制器(polarization controllers, PC1&PC2)用于产生非线性偏振旋转效应从而生成调 Q 脉冲。偏振无关隔离器(PI-ISO)则用于保证光信号在腔内的单向传播。波分复用器两端的尾纤(OFS980)长度为 0.435 m，腔内的净二阶色散约为-0.21 ps^2。

泵浦源为 980 nm 的台式激光器(OVLINK, Wuhan,

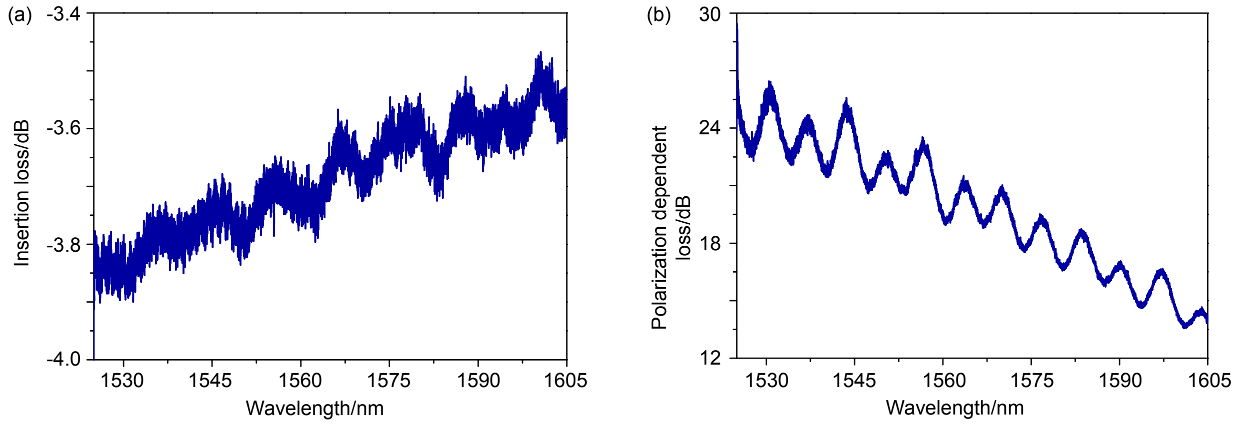

图 1 光谱范围在 1525 nm~1608 nm 时 45° 倾斜光纤光栅的损耗特性。(a) 插入损耗；(b) 偏振相关损耗响应

Fig. 1 Measured insertion loss of the 45° TFG from 1525 nm to 1608 nm. (a) Insertion loss; (b) PDL response

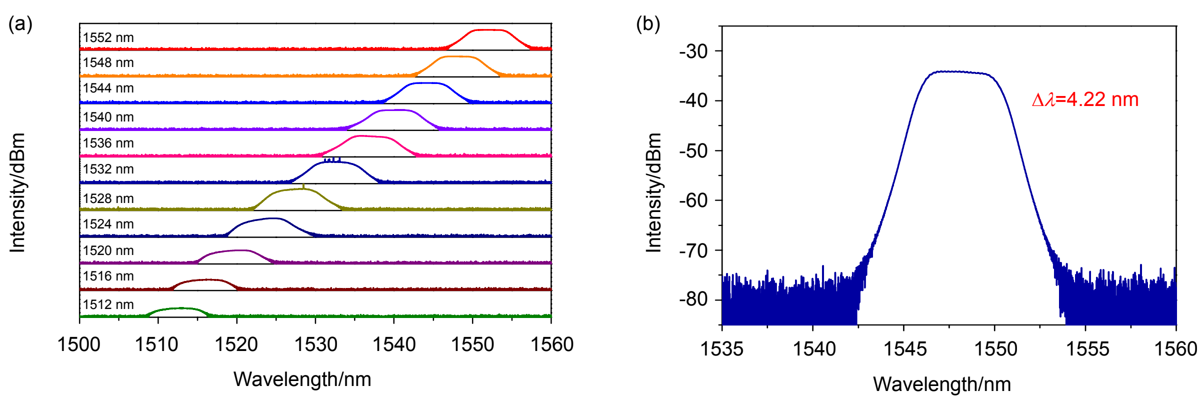

图 2 可调谐带通滤波器的光谱特性。(a) 1512 nm~1552 nm；(b) 1548 nm

Fig. 2 Spectral characteristics of tunable bandpass filter. (a) 1512 nm~1552 nm; (b) 1548 nm

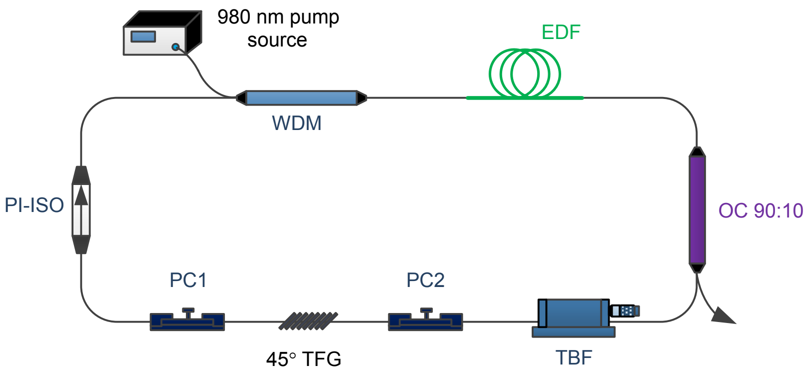

图 3 45°倾斜光纤光栅波长可调谐调 Q 光纤激光器示意图

Fig. 3 Schematic diagram of the wavelength-tunable Q-switched fiber laser based on a 45° tilted fiber grating

China)，其产生的泵浦光经过 980/1550 波分复用器(wavelength division multiplexing, WDM)进入激光腔内，激光在环形腔内沿顺时针方向单向传播，最终由一个 90:10 光纤耦合器(OC)的 10%端口输出。输出激光的光谱由光谱分析仪(OSA, Yokogawa AQ6370C)测量，脉冲序列以及射频谱则需要输出光通过 12.5 GHz 的光电探测器(PD, Newport 818-BB-51F)之后分别用带宽为 1 GHz，采样率为 5 GS/s 的示波器(OSC, Tektronix MSO4104)以及频谱分析仪(SSA, Siglent SSA 3032X)测得，输出功率由数字光功率计(PM, Yokogawa AQ2160-02)采集。

4 实验结果与讨论

在 106 mW 的泵浦功率下，我们得到了稳定的调 Q 脉冲输出，这一泵浦功率也是该激光器产生调 Q 的阈值功率。光信号通过 45°光纤光栅之后变换为线偏振光，45°光纤光栅两侧的偏振控制器用来补偿由于光纤非线性引起的偏振态旋转，由此产生的非线性偏振旋转效应让环形腔中的激光产生强度依赖损耗从而导致脉冲的生成。此时，铒离子的上能级将会积聚大量的粒子，当积累的能量以及激光辐射强度达到合适状态时，激光器就会输出调 Q 脉冲[29]。

由于掺铒光纤的增益带宽比较大，光谱带通滤波器又具有让特定波长范围内的光通过的特性，所以实验中可以用光谱带通滤波器来实现输出光谱的中心波长连续可调。

当把泵浦功率增加到 655 mW 时，适当调节偏振控制器以及带通滤波器之后，我们很容易观测到稳定的调 Q 脉冲。保持泵浦功率为 655 mW 不变，仅调节带通滤波器而不改变偏振控制器的状态，输出光谱的中心波长可以从 1512 nm 处连续移至 1552 nm 处，具体的光谱漂移现象如图 4(a)所示。光谱漂移过程中，1548 nm 处的调 Q 脉冲输出最为稳定，此时 3 dB 带宽为 1.45 nm，这由商用光谱带通滤波器的带通选择特性所决定的，如图 4(b)所示。保持输出激光的光谱中心波长为 1548 nm 不变，测量得到时域脉冲序列图以及单脉冲波形图分别如图 4(c)和图 4(d)所示，此时脉冲重复频率为 105 kHz，脉冲宽度为 4.2 μs，平均输出功率为 4.45 mW。频率范围设为 0~200 kHz 以及 0~500 kHz 的频谱如图 4(e)所示，此处调 Q 脉冲的信噪比为 39.89 dB。当中心波长靠近 1512 nm 或者 1552 nm 这两个极限时，激光器输出的调 Q 脉冲变得不稳定。这主要是由于 1512 nm 的增益较小，非线性效应不明显；另外，1552 nm 处的增益与 1548 nm 不同，因此在 1548 nm 处满足的非线性偏振旋转条件会在 1552 nm 受到一定程度的影响。

与锁模不同，调 Q 脉冲的重复频率与腔的长度无关，而与腔内的增益、损耗以及双折射效应有关。随着泵浦功率的增加，更多的粒子将被激发到增益介质的上能级上，这会使得输出调 Q 脉冲的累积时间与发射时间都变短，进而导致脉冲重复频率变高。本实验中，保持两个偏振控制器以及带通滤波器状态不变，光谱的中心波长仍然为 1548 nm 时，其平均输出功率以及重复频率与泵浦功率的关系如图 4(f)所示。泵浦功率从 106 mW 逐渐增加到 661 mW 的过程中，激光器的平均输出功率从 0.282 mW 逐渐增加到 4.884 mW，脉冲重复频率则从 23.7 kHz 逐渐增加到 119.0 kHz。

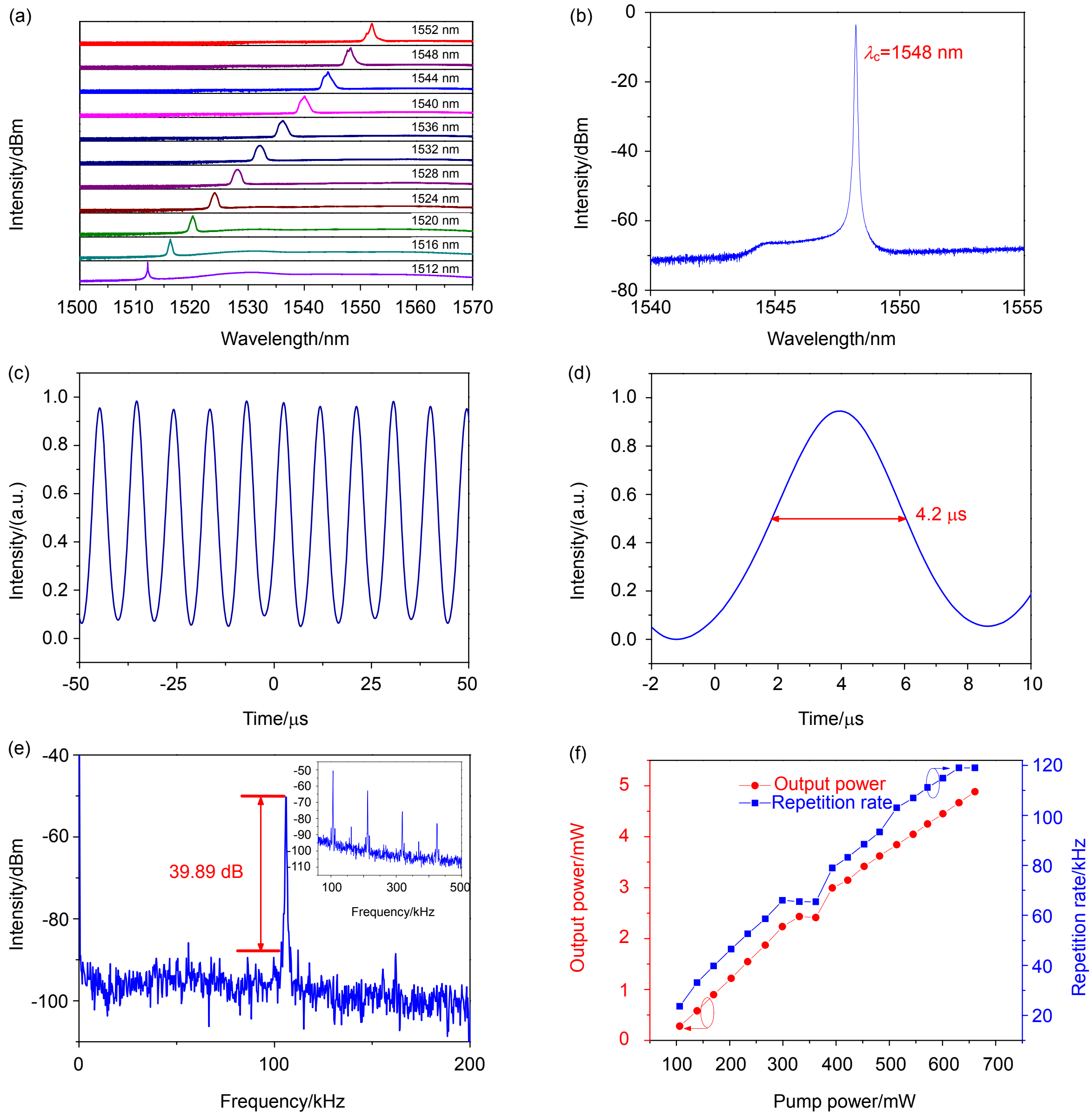

图 4　泵浦功率在 655 mW 下激光器的输出特性。(a) 光谱漂移；(b) 光谱；(c) 脉冲序列；(d) 单脉冲；(e) 频率范围为 200 kHz 的频谱图，插图是频率范围为 500 kHz 的频谱图；(f) 输出功率和重复频率与泵浦功率的关系

Fig. 4　Measured characteristics of Q-switched fiber laser under the pump power of 655 mW. (a) Optical spectrum shift; (b) Optical spectrum; (c) Pulse trains; (d) Profile; (e) RF spectrum with a 200 kHz span, inset presents the RF spectrum with a 500 kHz span; (f) The laser output power and repetition rate variations along with elevating pump power

5　结　论

本文报道了一台基于 45°倾斜光纤光栅与带通滤波器的连续可调谐全光纤调 Q 掺铒激光器。这也是迄今为止报道过的基于非线性偏振旋转效应和带通滤波器实现的可调谐调 Q 的光纤激光器中连续可调谐范围最宽的。此激光器中调 Q 脉冲的输出是基于 45°倾斜光纤光栅以及两个偏振控制器产生的非线性偏振旋转效应，同时维持了激光器的全光纤结构。调 Q 光谱的波长连续可调谐则通过调节光谱带通滤波器来实现。实验结果表明，波长可调谐的范围涵盖了 1512 nm 至 1552 nm。在泵浦功率为 655 mW 时，输出脉冲的重复频率为 105 kHz、平均输出功率为 4.45 mW、且信噪比为 39.89 dB。在同一调 Q 状态下，我们还将泵浦功率

从 106 mW 上升至 661 mW，得到的平均输出功率从 0.282 mW 逐渐增加到 4.884 mW，脉冲重复频率从 23.7 kHz 逐渐增加到 119.0 kHz。未来，我们希望将这种技术扩展到 1 μm、2 μm 等波段并搭建稳定的波长可调谐全光纤激光器作为加工、成像、非线性研究的种子源。

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Wavelength-tunable Q-switched fiber laser based on a 45° tilted fiber grating

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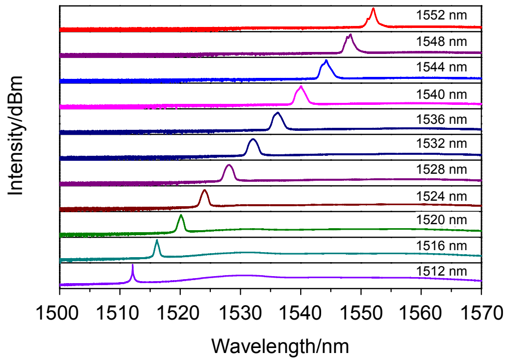

Optical spectrum shift

Overview: Wavelength tunable Q-switched fiber lasers have important applications in the fields of communication, medicine, ranging finding and laser processing. Generally speaking, Q-switched fiber lasers can be divided into two types using either active or passive system. There are several kinds of saturable absorber can be used to realize passively Q-switched in fiber lasers, including semiconductor saturable absorber mirrors (SESAMs), transition metal-doped crystals and single-wall carbon nanotubes (SWNTs). However, the method of using nonlinear polarization rotation (NPR) technology which is an artificial saturable absorber to realize passively Q-switched can not only maintain all-fiber structure of fiber lasers, but also change the width of Q-switched pulses by adjusting the states of polarization controllers. By regulating commercial bandpass filter, the central wavelength of the Q-switched pulses can be adjusted continuously in a larger range.

In this paper, a continuously tunable Q-switched all-fiber Er-doped laser based on a 45°-tilted fiber grating and tunable bandpass filter is demonstrated. The 45°-tilted fiber grating is used to achieve the nonlinear polarization rotation (NPR) along with two polarization controllers (PCs). In this experiment, the fiber grating is equivalent to an ideal in-fiber polarizer because it has strong polarization-dependent loss (PDL), then the Q-switched pulses can be easily observed by properly adjusting the polarization controllers. Under the pump power of 655 mW, stable Q-switched pulses with central wavelength of 1548 nm, average output power of 4.45 mW, repetition rate of 105 kHz, and signal to noise ratio (SNR) of 39.89 dB are obtained. Furthermore, the Q-switched optical spectrum can be continuously tuned from 1512 nm to 1552 nm by simply rotating the tunable bandpass filter with 655 mW pump power. As far as we know, this is the widest tunable range of tunable Q-switched fiber Lasers based on nonlinear polarization rotation effect and tunable bandpass filter.

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