

基于二硒化铌的1.5 μm 被动调Q光纤激光器

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摘 要

采用液相剥离法制备了具有优异的非线性光学响应、宽工作带宽的二硒化铌可饱和吸收体。将该可饱和吸收体应用到1.5 μm 光纤激光器中实现了被动调Q运转。在泵浦功率125 mW时, 此时调Q激光脉冲宽度4.1 μs , 重复频率39.6 kHz, 输出功率3.27 mW。随着泵浦功率增大时, 激光脉冲宽度下降, 重复频率上升。泵浦功率达到350 mW时, 获得重复频率最大78.4 kHz, 脉冲宽度最小2.3 μs , 此时激光中心波长1559.9 nm, 输出功率可达7.03 mW。其结果说明, 二硒化铌是一种优良的光学材料, 在超快非线性光学中具有重要的应用前景。

关键词

液相剥离法, 二硒化铌, 非线性光学, 光纤激光器, 光学材料

1.5 μm Passively Q-Switched Fiber Laser Based on Niobium Diselenide

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Abstract

The niobium diselenide saturable absorber with wide working bandwidth and excellent nonlinear

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optical response was prepared by liquid phase exfoliation. The niobium diselenide saturable absorber is applied to 1.5 μm fiber laser to realize passively Q-switched operation. When the pump power is 125 mW, the laser output power is 3.27 mW, the repetition rate and pulse width are 39.6 kHz and 4.1 μs . With the increase of pump power, the laser pulse width decreases and the repetition rate increases. When the pump power reaches 350 mW, the maximum repetition rate and minimum pulse width are 78.4 kHz and 2.3 μs , the central wavelength of the laser is 1559.9 nm, and the output power can reach 7.03 mW. The experimental results show that niobium diselenide is an excellent optical material, which has great application prospects in ultrafast nonlinear optics.

Keywords

Liquid Phase Exfoliation, Niobium Diselenide, Nonlinear Optics, Fiber Laser, Optical Material

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1. 引言

在精密加工、医疗诊断、材料加工和光谱学等各个领域都广泛使用了短脉冲全光纤激光器[1] [2]。调 Q 技术是实现激光脉冲输出的重要手段，它能将连续激光转变成微秒(μs)甚至纳秒(ns)使得脉冲能量和峰值功率成倍提升[3]。调 Q 技术分两种，一种是主动调 Q，在谐振腔内加入有源调制器，借助于外界输入信号来调节激光输出；另一种是将可饱和吸收体(SA)插入在谐振腔，其对光的吸收作用会随着入射光的增大而减小，依靠这种光学特性对光进行调制的被动调 Q。被动调 Q 技术由于效率高、成本低、易于集成等优点，是最为常见的方法之一[4] [5] [6]。

实现被动调 Q 的关键是依靠可饱和吸收体。传统的可饱和吸收体由于稳定性高、制备工艺成熟而在脉冲激光器中广泛应用，但其制备成本高、工作带宽窄[7]，所以探索廉价且性能优异的新型 SA 已成为不可忽视的工作。随着非线性光学材料的发展，二维材料因其新颖的电子和光学性能而受到广泛研究[8] [9] [10]。许多二维材料在可见光到中红外波段表现出对光的强烈饱和和吸收作用[11] [12]，比如石墨烯[13] [14]、黑磷(BP) [15] [16]、拓扑绝缘体(TIs) [17] [18]、MXenes [19] [20]和过渡金属二卤族化合物(TMDs) [21] [22] [23]等，特别是家族成员广泛的 TMDs 引起了广泛关注。TMDs 的化学式为 MX_2 ，其中硫属元素(Se、S、Te 等)为 X，过渡金属元素(W、Nb、Hf、Ta 等)为 M [24]。许多 TMDs 已经得到充分的研究[25] [26]，而具有快速的光电流响应和载流子迁移率等独特性能的二硒化铌(NbSe_2)研究还相对较少[27]，特别是作为 SA 在超快激光器的应用上。2018 年 YihuanShi 团队通过将 NbSe_2 量子点溶液滴到侧面抛光的光纤上，获得调 Q 激光输出，输出功率 4.44 mW、波长 1533 nm [28]；2021 年 PingHu 团队采用光驱动沉积法制备 NbSe_2 SA，在泵浦功率 515 mW 时，实现被动调 Q 运转，输出功率 3.1 mW，波长 1560.38 nm [29]。

我们采用液相剥离法制备了 NbSe_2 -PVA SA，把它插入优化设计的掺铒光纤激光器谐振腔，成功地实现了被动调 Q 运转。泵浦功率增大到 350 mW 时，测得 7.03 mW 的输出功率，78.4 kHz 重复频率和 2.3 μs 脉冲宽度，在此条件下计算得 89.7 nJ 单脉冲能量和 39.0 mW 峰值功率。测量激光器一小时的输出功率变化，计算得激光器 RMS 功率不稳定性小于 1%。

2. NbSe_2 可饱和吸收体制备

实验采用液相剥离法制备 NbSe_2 -PVA SA，制备过程如图 1 所示。首先，在 20 ml 去离子水(DI)中加

入 20 mg NbSe_2 粉末, 充分搅拌, 然后放到超声波清洗器中进行超声液相剥离 6 小时。其次, 将混合物以 5000 rpm 的速度离心 30 分钟, 选取 1/2 的上层清液, 加入 200 mg 聚乙烯醇(PVA)并超声 1 小时混合溶液, 以确保混合均匀, NbSe_2 -PVA 纳米片溶液就制备完成了。最后, 将上述操作制得的 NbSe_2 -PVA 纳米片溶液倒入培养皿中, 放到 25℃ 的通风柜里干燥一晚形成薄膜, 然后将薄膜转移到光纤连接器端面上, 这样就制得我们实验所用的 NbSe_2 -PVA SA。

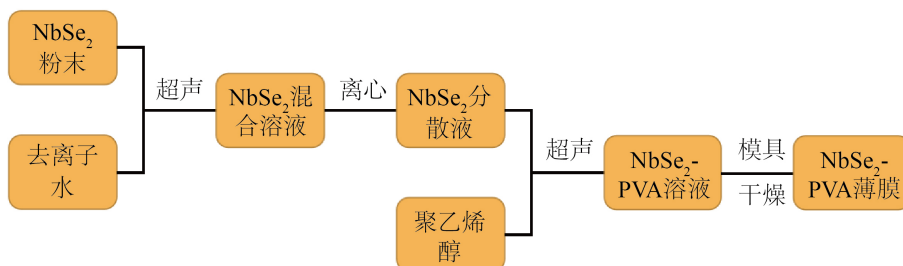


Figure 1. Complete process of preparing NbSe_2 -PVA saturable absorber
图 1. NbSe_2 -PVA 可饱和吸收体的制备过程

3. 实验装置

图 2 为实验用激光器装置图。掺铒光纤是激光器增益光纤(EDF), 长度为 0.7 m。泵浦源(LD)为半导体激光器, 输出激光中心波长 976 nm。976/1550 nm 的波分复用器(WDM)将泵浦光耦合进谐振腔内。激光腔内插入偏振不敏感隔离器(PI-ISO)确保腔内的光可以沿一个方向传播。为了能调节谐振腔的偏振态, 加入一个三环偏振控制器(PC)。可饱和吸收体(SA)通过一个法兰夹在两个光纤跳线之间插入谐振腔里。谐振腔采用环形腔结构, 90/10 的输出耦合器(OC)用来将激光分流, 10% 的激光输出, 用测试设备来检测激光输出性能, 90% 的激光继续在环形腔内循环。

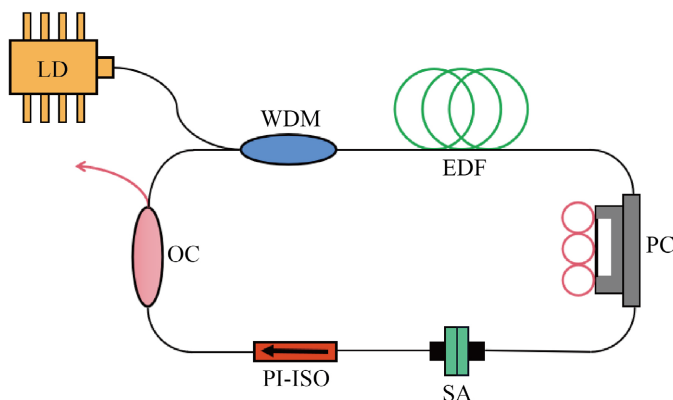


Figure 2. Diagram of Q-switched fiber laser based on NbSe_2 -PVA SA
图 2. 基于 NbSe_2 -PVA SA 的调 Q 光纤激光器示意图

4. 实验结果

实验过程中, 转动偏振控制器改变谐振腔内的偏振态, 同时增加泵浦功率, 通过 5 GHz 光电探头 (Thorlabs, DET08CFC/M) 以及 500 MHz 带宽、5 GSa/s 采样率的示波器 (KEYSIGHT DSOX3052T) 观测激光器输出脉冲。改变泵浦功率, 当达到 125 mW 时, 我们可以从示波器显示屏上清楚的看到激光器的输出从连续光变成了脉冲光。当泵浦功率增加到 350 mW 的时候, 调 Q 激光都能维持稳定状态。不同泵浦功

率下的输出脉冲序列如图 3 所示。

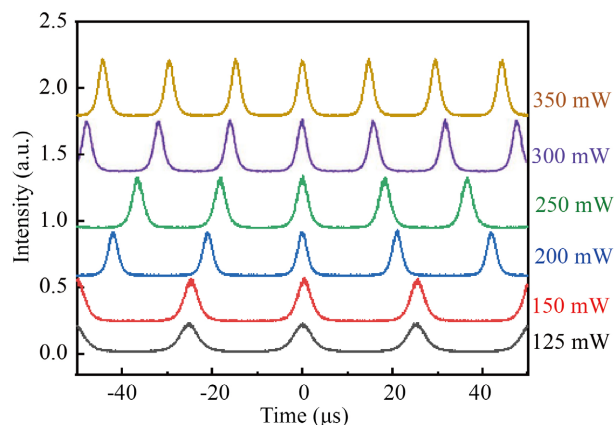


Figure 3. Diagram of pulse train under different pump power
图 3. 不同泵浦功率下脉冲序列图

图 4 为泵浦功率 350 mW 的激光器输出脉冲特性图。此时重复频率最大为 78.4 kHz，脉冲间隔 12.75 μ s，脉冲最小宽度 2.3 μ s。借助于分辨率 0.06 nm 的光谱分析仪(Agilent 86142B)对激光进行光谱测量，测得输出激光中心波长为 1559.9 nm。采用射频信号分析仪(Agilent N9020A)进一步测量输出激光的频谱，在 78.4 kHz 处发现一处高频信号，这也再次验证了脉冲重复频率，除此之外，还可以看出激光信噪比为 47 dB。

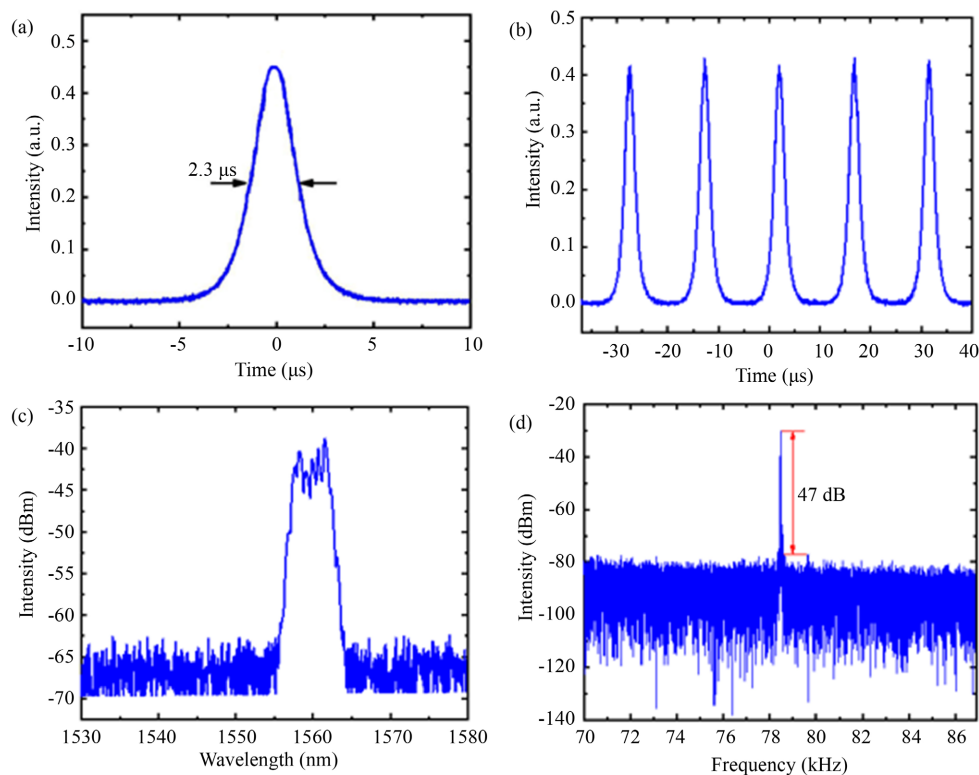


Figure 4. Laser output characteristics at 350 mW pump power
图 4. 泵浦功率处于 350 mW 下激光输出特性图

图 5 为泵浦功率增加时激光器的脉冲宽度和重复频率之间的关系。可以看出,随着泵浦功率的增加,重复频率增加,脉宽减小。当泵浦功率从 125 mW 增加到 350 mW 时,重复频率从 39.6 kHz 增加到 78.4 kHz,脉冲宽度从 4.1 μs 减小到 2.3 μs 。图 6 为脉冲能量和输出功率与泵浦功率的关系。泵浦功率 350 mW 时,

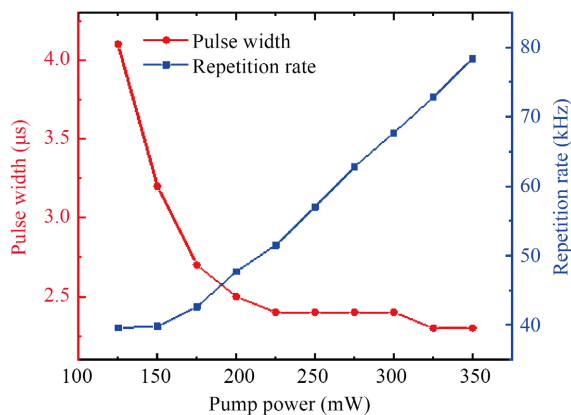


Figure 5. Diagram of repetition rate and pulse width versus pump power

图 5. 重复频率和脉冲宽度与泵浦功率之间的关系图

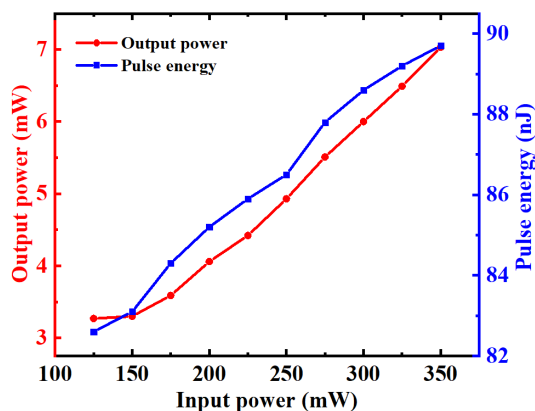


Figure 6. Diagram of pulse energy and output power versus pump power

图 6. 脉冲能量和输出功率与泵浦功率之间的关系图

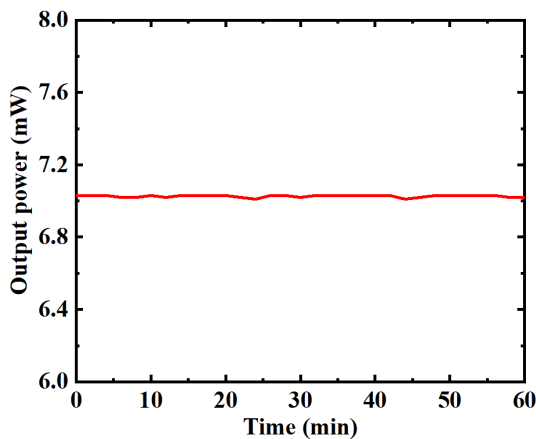


Figure 7. Schematic diagram of laser output power within one hour

图 7. 激光输出功率在 1 小时内变化示意图

输出 7.03 mW 最大输出功率, 89.7 nJ 脉冲能量, 对应的峰值功率 39.0 mW。为了验证调 Q 掺铈光纤激光器中 NbSe₂-PVA SA 的作用, 保持腔长不变, 谐振腔内取出可饱和吸收体, 此时无论怎样调节 PC 和改变泵浦功率, 示波器上都没有检测到调 Q 激光。结果证实, 激光器输出的脉冲光确实是我们制备的 NbSe₂-PVA SA 引起的。

为了表征激光器的稳定性, 我们在泵浦功率 350 mW 下观察其一小时内功率输出变化。测得激光器在 1 小时内的输出功率不稳定性小于 1%, 图 7 为输出功率测量结果。

5. 结论

实验所用 NbSe₂-PVA 可饱和吸收体采用液相剥离法制备, 将其应用于 1.5 μm 光纤激光器中, 由于可饱和吸收体对光的可饱和吸收特性, 激光器实现稳定地被动调 Q 运转。在泵浦功率 125 mW 时激光器开始进入调 Q 状态, 此时重复频率和脉冲宽度为 39.6 kHz 和 4.1 μs。继续增大泵浦功率到 350 mW, 此时重复频率增大到 78.4 kHz, 脉冲宽度减小到 2.3 μs, 最大输出功率达到 7.03 mW, 相应的脉冲能量和峰值功率为 89.7 nJ 和 39.0 mW, 输出激光中心波长为 1559.9 nm。实验结果表明, NbSe₂ 具有优异的非线性光学特性, 在超快光子器件的应用上有广阔的发展空间。

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