机械剥离石墨烯被动谐波锁模掺铒光纤激光器

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摘要 基于机械剥离方法,即通过胶带反复剥离高定向热解石墨,制备得到少层石墨烯,并将其作为可饱和吸收体实现了被动谐波锁模掺铒光纤激光器。在抽运功率约135 mW时,获得了中心波长1568.3 nm,脉冲宽度1.82 ps,3 dB带宽1.7 nm,重复频率1.646 MHz的基频锁模激光输出。通过增加抽运功率和调节腔内偏振,可以获得谐波锁模,谐波阶数最高达到基频的47阶(77.36 MHz)。同时,研究了不同阶谐波锁模时,输出功率、脉冲宽度和单脉冲能量的变化。

关键词 激光器; 超快光纤激光器; 谐波锁模; 石墨烯; 机械剥离
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Passive Harmonic Mode-Locking in Er-Doped Fiber Laser Based on Mechanical Exfoliated Graphene Saturable Absorber

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Abstract Passive harmonic mode-locking of erbium-doped fiber laser with graphene as a saturable absorber is proposed. Graphene saturable absorber is obtained via mechanical exfoliation method by peeling highly oriented pyrolytic graphite repeatedly. When the pump power is 135 mW, the laser operates at fundamental repetition rate of 1.646 MHz with pulse duration of 1.82 ps and 3 dB bandwidth of 1.7 nm. With the pump power and adjusting polarization in the cavity appropriately increasing, the laser operates at several harmonics of fundamental repetition rate and the highest repetition rate achieved is 77.36 MHz, which corresponds to the 47th harmonic. The output power, pulse duration and single pulse energy for different harmonics have been studied.

Key words lasers; ultrafast fiber laser; harmonic mode-locking; graphene; mechanical exfoliation
OCIS codes 140.7090; 190.2620; 160.4330; 220.4000

1 引 言

高重复频率的锁模激光器在高速光通信、光谱学、精确计量等领域有着广泛的应用。为了在被动锁模光纤激光器中产生高重复频率的脉冲,一个有效的方法是缩短腔长。通过缩短腔长,可以实现高重复频率,但是器件制作的难度大大增加。通过谐波锁模的方法同样可以获得高重复频率的脉冲激光输出。从1972年被Becker等[1]首次提出之后,各种被动锁模方式都被用来产生谐波锁模输出,如非线性放大环形镜[2],非线性偏振旋转[3-4]和半导体可饱和吸收镜[5-6]等。

伴随着新型纳米材料的出现,单壁碳纳米管(CNT)由于其高非线性和快的恢复时间,已经作为新型的可饱和吸收体引入到激光器中[7-12],并且应用于谐波锁模[13-15]中。一种由单层碳原子堆积而成的二维蜂窝状新型碳材料——石墨烯的发现引起了广泛的关注[16-19]。自从第一台以石墨烯为可饱和吸收体的激光器面世以

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来[20],石墨烯由于其具有超宽带吸收,大的调制深度,低的可饱和吸收阈值,高损伤阈值等优点,已经被广泛应用在调 Q 和锁模激光器的研究中[21-36]。最近,基于石墨烯的谐波锁模也有所报道。Sotor等[37]利用机械剥离的方法制备得到石墨烯可饱和吸收体,并获得最高46阶(800 MHz)的谐波锁模输出。在此基础上,通过改进腔的结构,得到了最高21阶(2.22 GHz)的谐波锁模输出[38]。Meng等[39]利用石墨烯分散液制成薄膜,再通过化学剥离的方法得到石墨烯,并得到了最高46阶(0.49 GHz)的谐波锁模输出。Feng等[40]通过机械剥离的方法得到石墨烯可饱和吸收体,比较系统地研究了石墨烯锁模掺铒光纤激光器中不同的孤子态。

本文基于机械剥离方法,利用胶带反复剥离高定向热解石墨(HOPG),制备得到石墨烯,并利用范德华力将其吸附于光纤头上作为可饱和吸收体实现了被动谐波锁模掺铒光纤激光器。在抽运功率约135 mW时,获得了中心波长1568.3 nm,脉冲宽度1.82 ps,3 dB带宽1.7 nm,重复频率1.646 MHz的基频锁模激光输出。通过增加抽运功率和调节腔内偏振,可以获得谐波锁模,谐波阶数最高达到基频的47阶(77.36 MHz)。同时,研究了在不同阶谐波锁模的条件下,输出功率、脉冲宽度和单脉冲能量的变化。

2 实验装置

石墨烯通过机械剥离方法获得。将高定向热解石墨(HOPG)放置于透明胶带上,反复挤压,撕离,最后得到多层的石墨烯。接着,将一个标准的洁净的FC/PC型光纤连接器压在多层石墨烯上,由于较强的范德华力,少层的石墨烯就会吸附在光纤插芯端面上。然后,用一个法兰盘将其与另外一个FC/PC型光纤接头连接起来,熔接至腔内作为可饱和吸收体。

激光器实验装置如图1所示,总腔长约为117 m,整个激光腔主要包括:1 m高掺杂的掺铒光纤(EDF, LIEKKI Er80-8/125),群速度色散(GVD)在1550 nm处为−20 ps^2/km,峰值吸收在1530 nm处为80 dB/m;105 m的标准单模光纤(SMF),GVD为−23 ps^2/km;光耦合器(OC)耦合比为10:90,10%的一端作为输出端口;980/1550 nm波分复用器(WDM)用来将抽运光和反馈光耦合进腔内;偏振无关隔离器(PII)保证腔内激光的单向传输;偏振控制器(PC)用来调节腔内双折射,优化输出。抽运源的中心波长为975 nm,最大输出功率为500 mW。输出特性由光谱仪(Ando AQ-6317B),示波器(Tektronix TDS3054B)和商用的二次谐波自相关仪来测量。

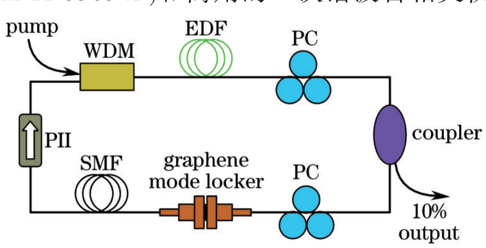

图1 光纤环形激光器示意图

Fig.1 Schematic setup of fiber ring laser

3 实验结果及讨论

通过适当调节PC,激光器自启动锁模阈值为131 mW。图2给出了抽运功率为135 mW时激光器的基频孤子输出特性。图2(a)为输出的时域波形图,其重复频率为1.646 MHz,与根据 $f_c = c/(nL)$ 公式计算得出的腔的基频吻合,证明其为锁模脉冲;图2(b)为输出的光谱图,可见光谱中心两侧有清晰的Kelly边带出现,表明输出脉冲为光孤子,其中心波长为1568.3 nm,3 dB光谱带宽为1.7 nm;图2(c)为对应的孤子脉冲自相关迹,其半峰全宽为2.809 ps,通过双曲正割函数拟合后得到脉宽为1.82 ps。由上述参数,可得时间带宽积为0.377,由此可以看出,其为近传输极限脉冲。

进一步增加抽运功率,单孤子脉冲分裂成多孤子脉冲,这些脉冲的间隔不是固定的,随机分布在腔内。但是通过调节偏振控制器和抽运功率,在某些特定的情况下,孤子逐步分开,自主地建立起一个稳定、有序的状态,最终有规律地分布在腔内,并且各个孤子脉冲的间隔保持一致,而重复频率会比腔的基频高出很多[41-42],得到谐波锁模。

实验中,在不同的抽运功率下,通过适当地调节PC,得到了不同阶数的谐波锁模,当抽运功率分别为

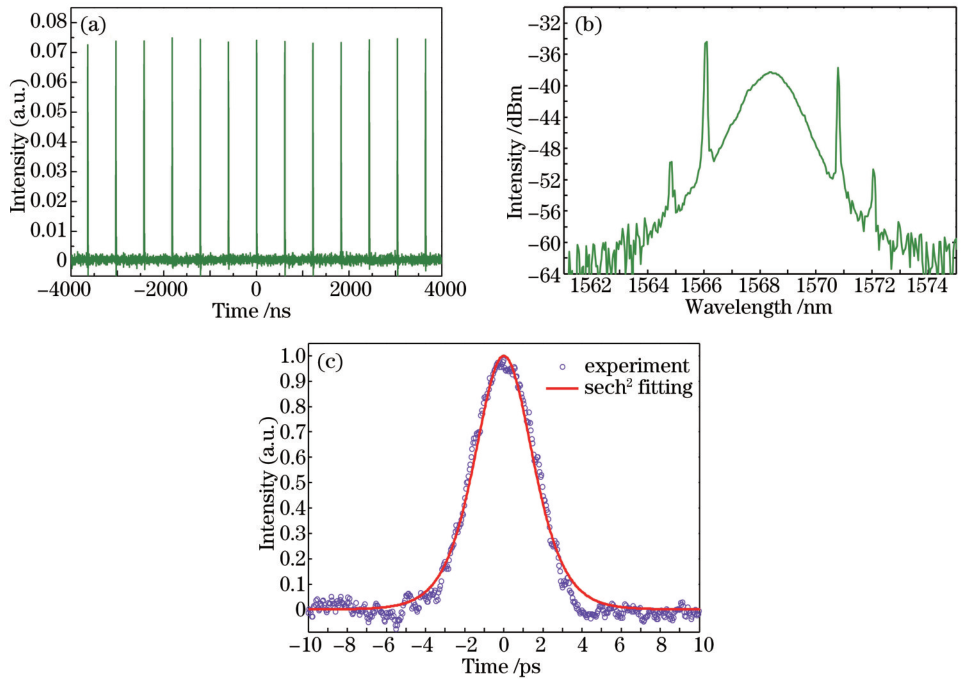

图2 光纤激光器典型的基频孤子输出。(a) 输出脉冲串; (b) 输出光谱图及其(c) 相应的自相关迹及其双曲正割拟合曲线

Fig.2 Typical fundamental soliton emission of fiber laser. (a) Output pulse train; (b) output spectrum and (c) corresponding autocorrelation trace and its hyperbolic secant function fitting curve

217,262,276,290,329,343,362 mW时获得了11,15,17,19,27,36,47阶的谐波锁模,对应的重复率分别为18.12,24.68,27.98,31.26,44.43,60.90,77.36 MHz。图3给出了11,19,27,47阶的输出特性,其中图3(a),(c),(e),(g)为其时域图,图3(b),(d),(f),(h)为对应的光谱图。时域中,不同阶数谐波中的脉冲间隔不等,在相同的往返激光腔所需的时间内,有不同个数的脉冲,即不同阶数的谐波锁模脉冲。值得注意的是在时域中,脉冲峰值出现了调制,这是由孤子激光器中色散波的调制不稳定性造成的。在孤子激光器中,色散波的强度超过产生调制不稳定性效应的阈值后,它们就会变得不稳定,会产生新的频率成分,即出现亚边带,因此孤子脉冲的峰值出现一定的幅度调制[43]。对应的光谱在短波长处出现的亚边带印证了这一点,另外从图中可看出亚边带的峰值越高,对应时域输出的调制强度越大。在调节PC的过程中,在连续波(CW)出现后才能得到谐波锁模态,CW在高次谐波锁模的产生过程中发挥着重要的作用[35]。

不同阶谐波锁模时,输出功率、脉冲宽度和单脉冲能量的变化关系如图4所示。图4(a)给出了谐波锁模阶数和输出功率随抽运功率的变化关系,可以看出,谐波锁模阶数和输出功率均随着抽运功率的提高而增大,输出功率与抽运功率呈现线性关系。图4(b)展示了脉冲宽度和单脉冲能量与谐波锁模阶数之间的关系,发现不同阶数的谐波锁模脉冲具有相近的脉冲宽度,处于1.83~1.98 ps之间;单脉冲能量在35.8~65.6 pJ之间变化,该能量值高于文献[13]和[14]报道的结果。当抽运功率增加到一定程度时,受到峰值功率钳制效应的限制,孤子的脉冲峰值功率不会随着抽运功率的增加而增加,而背景噪声会在此时被放大,在可饱和吸收体的作用下产生新的孤子[44]。而新的孤子初始能量较低,由于新的孤子和原来的孤子存在增益竞争,最终所有的孤子都会具有相同的脉冲宽度和峰值功率。随着抽运功率进一步增加,更高阶的孤子以同样方式产生并达到稳态。

4　结　　论

报道了石墨烯作为可饱和吸收体的被动谐波锁模掺铒光纤激光器。基于机械剥离的方法,制备得到少层石墨烯,并将其吸附到光纤插芯作为可饱和吸收体。在抽运功率约131 mW时,获得了中心波长1568.3 nm,脉冲宽度1.82 ps,光谱半峰全宽1.7 nm,重复频率1.646 MHz的基频锁模激光输出。通过增加抽运功率和调节腔内偏振,获得11,15,17,19,27,36,47阶的谐波锁模输出。同时,研究了不同阶谐波锁模时,输出功率、脉冲宽度和单脉冲能量的变化关系。其中,输出功率与输入功率呈现线性关系,脉冲宽度在1.83~1.98 ps之间变化,单脉冲能量在35.8~65.6 pJ之间变化。

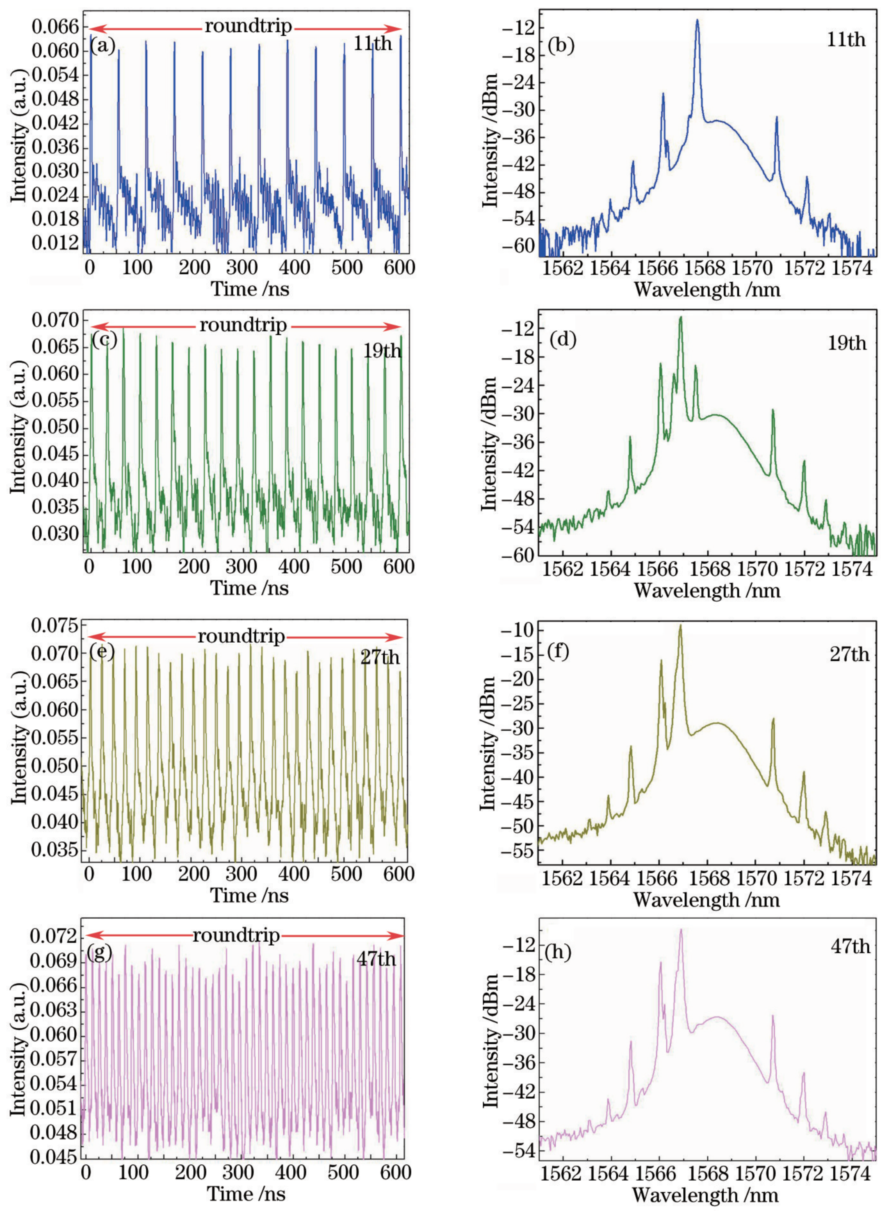

图3 谐波锁模输出脉冲串及对应的光谱。(a),(c),(e)(g)时域图; (b),(d),(e),(f)光谱图

Fig.3 Output pulse trains and corresponding spectrum of harmonic mode-locking. (a),(c),(e),(g) Time domain; (b),(d),(e),(f) spectra

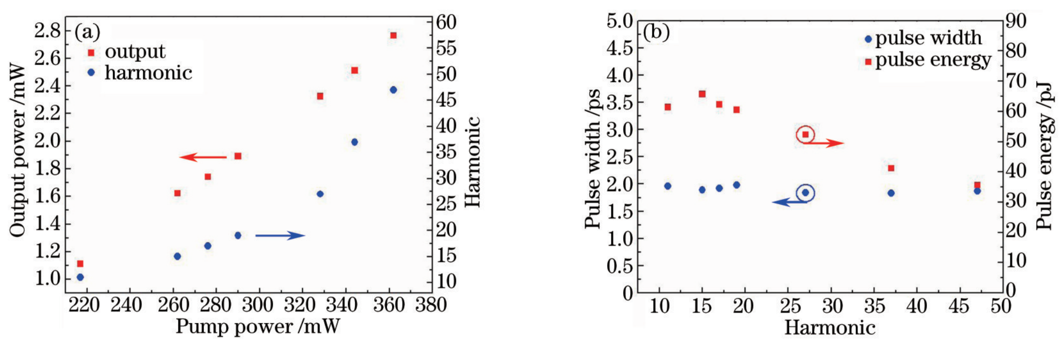

图4 不同阶数谐波锁模时,输出功率、脉冲宽度和单脉冲能量的变化。 (a)平均输出功率及谐波阶数随抽运功率的变化; (b) 脉冲宽度和单脉冲能量随谐波阶数的变化

Fig.4 Output power, pulse duration and single pulse energy at different harmonics mode-locking. (a) Average output power and number of harmonics versus pump power; (b) pulse duration and single pulse energy versus number of harmonics

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