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基于抛物线演化的宽光谱光纤啁啾脉冲放大系统

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摘　要:为了满足光纤激光器在宽光谱高能量应用领域的要求,搭建了一种结构紧凑的光纤型宽光谱啁啾脉冲放大系统。将色散管理型锁模激光器产生的高斯型脉冲作为种子源,注入到正色散掺铒光纤放大器中进行自相似放大,脉冲将逐渐演化成抛物线型,此过程中脉冲的谱宽和能量都迅速增大。随后脉冲经色散补偿光纤的时域展宽,双包层铒镱共掺光纤的功率放大,透射光栅对压缩后实现了高能量的宽光谱输出。并结合理论模拟,优化了激光器的各元件参数,最终在中心波长 1 560 nm 处实现了光谱宽度为 30 nm,平均功率为 1.3 W,脉宽为 587 fs,重复频率为 40.1 MHz 的宽光谱高能量激光输出。该激光器结构紧凑,稳定性好,对光学频率梳、光通信等应用领域具有一定研究价值。

关键词:啁啾脉冲放大;自相似放大;宽光谱;掺铒光纤;铒镱共掺光纤

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0　引言

光纤激光器由于高稳定性、高光束质量、结构紧凑等特点,在众多研究领域中受到广泛关注[1-3]。工作在 1 550 nm 处的高能量超快光纤激光器由于在通讯波长处的低衰减,价格便宜等特点被广泛应用于超快光谱学、精密材料加工以及太赫兹产生等研究领域[4-6]。而如何获得高能量脉冲也成为光纤激光器的研究热点。为了获得高能量脉冲,通常需要将增益光纤作为放大器,但将超短脉冲直接进行放大时由于高峰值功率会积累大量的非线性效应,例如自相位调制(Self-Phase Modulation, SPM)、受激拉曼散射等,从而降低光束质量[7-8]。为了避免强非线性,常用的一种解决方法是在放大前引入啁啾从而将脉冲宽度增大,降低峰值功率强度,随后利用光栅对等压缩器件对脉冲去啁啾以获得高能量的超短脉冲。这种放大方式也被称为啁啾脉冲放大(Chirped-Pulse Amplification, CPA)[9-10]。

近年来研究人员报道了一些 1 550 nm 波长处的高能量全光纤 CPA 系统。MORIN F 等[11]提出了一种将大模场面积的铒镱共掺光纤(Er/Yb Co-Doped Fiber, EYDF)作为放大器的 CPA 系统,使用色散补偿光纤(Dispersion Compensating Fiber, DCF)作为展宽器,光栅对作为压缩器,实现了脉宽 605 fs,脉冲能量 1.5 μJ 的激光输出。DAI W 等[12]选用碳纳米管锁模激光器作为种子源,并采用基于 EYDF 的二级放大结构对脉冲进行放大,经光栅对压缩后产生了平均功率为 3.4 W,脉宽为 765 fs 的脉冲输出。同样 PAVLOV I 等[13]使用 EYDF 作为功率放大器,脉冲经光纤展宽器展宽后再进行两级放大,最后压缩输出的脉冲平均功率为 10 W,脉宽为 450 fs。在以上报道中,研究人员都是利用 EYDF 去实现高能量脉冲输出,以此获得的脉冲光谱半高全宽都限制在 5~15 nm 范围内。到目前为止,在波长 1 550 nm 处实现光谱宽度高于 30 nm 的全光纤型 CPA 激光器鲜有报道。

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一些产生宽光谱脉冲的方法，例如使用类噪声锁模[14-15]、非线性光纤[16-17]、Mamyshev谐振腔[18]等，虽然均可实现宽光谱脉冲输出，但是由于脉冲不可压缩，参数结构复杂或者不够稳定等限制，不适于简易型CPA系统。在本文中，我们将自相似放大和CPA相结合，在1.55 μm处实现了一种结构紧凑的宽光谱瓦量级光纤激光器。其中种子源采用基于碳纳米管锁模的色散管理腔，可产生无Kelly边带的高斯型脉冲。根据自相似放大理论，脉冲在正色散掺铒光纤放大器中谱宽和脉宽都将增大，并演化成抛物线型，以此获得的宽光谱脉冲再经DCF展宽，10/125双包层铒镱共掺光纤（Double-Clad Erbium-Ytterbium Co-Doped Fiber，DC-EYDF）放大后，在40.1 MHz的重复频率下实现了光谱宽度为30 nm，平均功率为1.3 W的激光输出，最后通过透射光栅对压缩后的最窄脉宽为587 fs。

1 实验装置与原理

宽光谱CPA系统实验装置图如图1所示，它由全光纤种子源、光纤展宽器、主功率放大器、光栅压缩器组成。其中种子源为环形谐振腔结构，包括碳纳米管可饱和吸收体（Carbon Nanotubes Saturable Absorber，CNT-SA）、掺铒光纤（Erbium-Doped Fiber，EDF）、单模光纤（Single-Mode Fiber，SMF）、色散补偿光纤、波分复用器（Wavelength Division Multiplexer，WDM）和隔离器构成的二合一器件以及耦合器（Optical Coupler，OC）。其中二合一器件用来耦合980 nm泵浦光并保证激光在腔内的单向传输。OC的分束比为30:70，确保输出端有较大的输出功率。

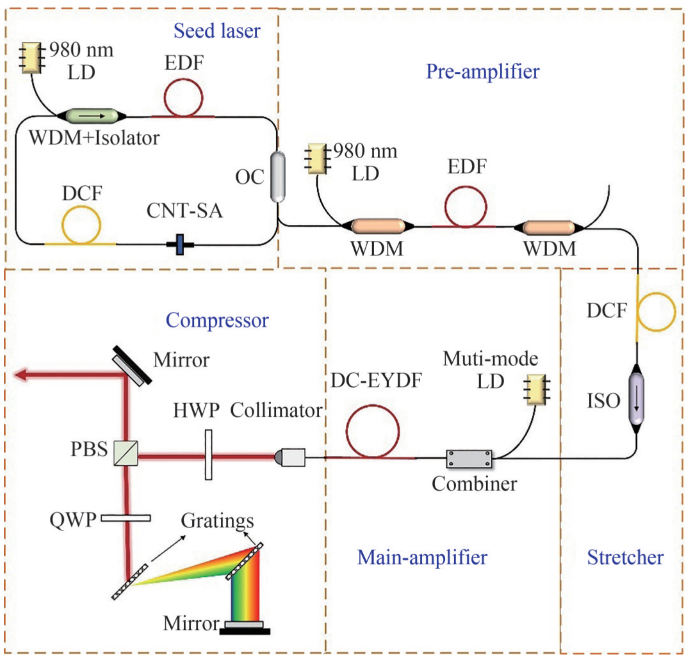


图1 宽光谱啁啾脉冲放大激光器实验装置

Fig. 1 Experimental setup of the broadband chirped-pulse amplification laser

种子源的输出脉冲首先注入到正色散掺铒光纤进行放大，在放大过程中高斯型脉冲在光纤色散以及非线性效应的共同作用下会逐渐演化成抛物线型，谱宽以及脉宽都将增大，实现自相似演化。随后WDM可用来滤掉多余的980 nm泵浦光。接着使用DCF对脉冲进行展宽，并使用隔离器阻止反向光对谐振腔的影响。第二级放大器采用10/125的DC-EYDF，最大功率为9 W的泵浦光通过1×2的合束器耦合进放大器。最后一级中，通过准直器输出的放大脉冲经由刻线密度为966 lines/mm的透射型光栅对进行压缩。光栅对平行放置且脉冲以Littrow角入射时可确保92%的最大衍射效率。反射镜可保证光束往返通过光栅对以缩短光栅对间距。为了分离压缩光和入射光，可通过半波片以及四分之一波片调节光束偏振态使得压缩光从偏振分束器的另一端输出。

为了对后续实验提供理论指导，首先对宽光谱CPA系统进行了理论模拟，脉冲在光纤中的传输可通过非线性薛定谔方程表示为[19]

$$\frac{\partial u}{\partial z}=-\mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 u}{\partial t^2}+\frac{g}{2}u+\mathrm{i}\gamma|u|^2u+\frac{g}{2\Omega_g}\frac{\partial^2 u}{\partial t^2} \tag{1}$$

式中,u为脉冲包络函数,z和t分别代表传输距离以及时间,β_2代表二阶色散系数,Ω_g和g分别为增益带宽以及增益系数。对于EDF,增益系数可表示为

$$g=g_0\exp\left(-\frac{E_{\mathrm{p}}}{E_{\mathrm{s}}}\right) \tag{2}$$

式中,g_0为小信号增益系数,E_{s}为增益饱和能量,E_{p}为脉冲能量。基于碳纳米管的可饱和体模型可表示为

$$T=1-\alpha_0-\frac{\alpha}{1+\dfrac{P}{P_{\mathrm{sat}}}} \tag{3}$$

式中,α_0为未饱和损耗,α为调制深度,P为瞬时脉冲功率,P_{sat}为饱和功率。

依托分步傅里叶算法,将激光器内的所有器件根据实验装置依次分布在激光腔内。然后采用脉冲追迹法模拟脉冲在腔内的运转情况。在仿真中我们采用预设置的小信号高斯型脉冲作为输入,当信号在腔内运转一周后,将其结果作为下一个循环的起始信号。在适当的腔内参数和误差控制下,经过100~1 000次循环后,最终就会得到稳定的锁模脉冲输出。

仿真模型中所使用的参数为:g_0=3 dB/m,E_{s}=12 pJ,Ω_g=30 nm,对于EDF,γ=4.5 W^{-1}km^{-1},β_2=20 ps^2/km;对于SMF,γ=1.3 W^{-1}km^{-1},β_2=−21.6 ps^2/km;对于DCF,γ=5 W^{-1}km^{-1},β_2=120 ps^2/km;对于DC-EYDF,γ=0.8 W^{-1}km^{-1},β_2=20 ps^2/km;对于光栅对,β_2=−9.1×10^3 ps^2/km。谐振腔内的SMF、EDF以及DCF的长度分别为4.2 m,0.5 m,0.42 m。谐振腔外的EDF、DCF以及DC-EYDF的长度分别为10 m、15 m、2.3 m。光栅对间距设置为22 cm。

模拟计算的色散管理孤子时域输出如图2(a)所示,脉冲宽度为524 fs并带有线性啁啾。图2(b)为预放大器到压缩器之间脉冲脉宽以及谱宽的演化,其中点a~d的值分别代表种子源、预放大器、展宽器、主放大

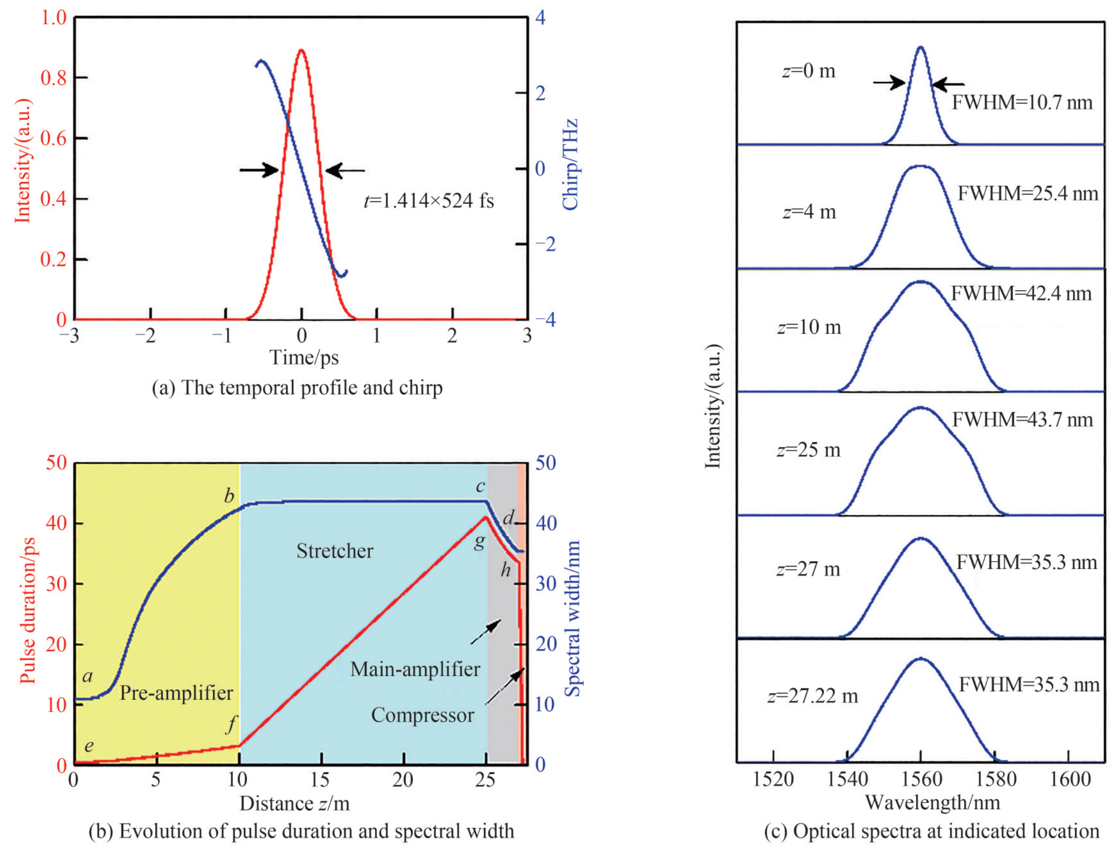


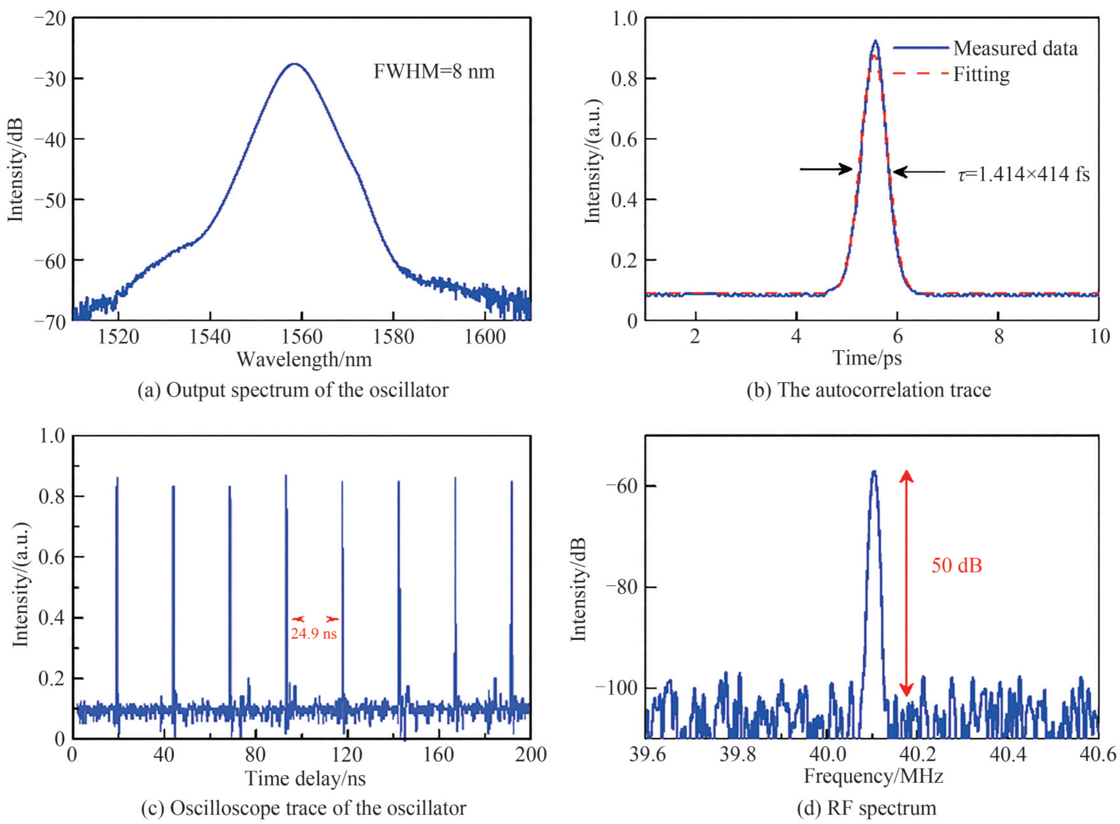
图2 宽光谱啁啾脉冲放大激光器理论模拟特性

Fig. 2 The theoretical simulation characteristics of broadband chirped-pulse amplification laser

器处的输出谱宽大小，点 $e\sim h$ 的值则代表相应位置处的脉宽大小。可以观察到脉冲在正色散EDF中放大时脉宽和谱宽迅速增大，在展宽光纤中脉宽变大，而谱宽几乎不变，随后在主放大器中由于增益窄化效应，脉宽和谱宽都减小，最后经压缩器后脉冲被压缩至230 fs。为了进一步观察此过程中的光谱演化，绘制了如图2(c)所示的脉冲在腔内不同位置处的光谱图。

2　结果与讨论

实验中，根据模拟结果选择了最佳的器件参数，搭建了图1所示的宽光谱啁啾脉冲放大系统。色散管理腔的EDF(Liekki, $\beta_2=1.148\ \mathrm{ps^2/cm}$)长为0.5 m，DCF(dispersion～−160 ps/(nm·km))长为0.42 m，SMF($\beta_2=-2.168\ \mathrm{ps^2/cm}$)长为4.2 m，腔内总腔长约为5.1 m，对应于40.1 MHz的重复频率，腔内总色散为0.036 4 $\mathrm{ps^2}$，符合色散管理孤子的产生条件。将色散管理种子源的泵浦功率调节为120 mW，此时可得到稳定的锁模孤子，输出功率为2.54 mW。种子源的输出光谱如图3(a)所示，其中心波长位于1 560 nm附近，半高全宽为8 nm，对应于图2(b)中点 a 处的值，光谱为高斯型且没有Kelly边带。为了表征脉冲宽度，使用自相关仪(APE, Pulse-check 50)对输出脉冲进行测量[20]，结果如图3(b)所示，高斯拟合后的脉宽为414 fs，与图2(b)中的点 e 对应。图3(c)为示波器测量的时域脉冲，可计算出脉冲序列的时域间隔为24.9 ns。脉冲的信噪比可由频谱分析仪测量，如图3(d)所示，此时输出信噪比为50 dB，反映了较好的腔内锁模稳定性。



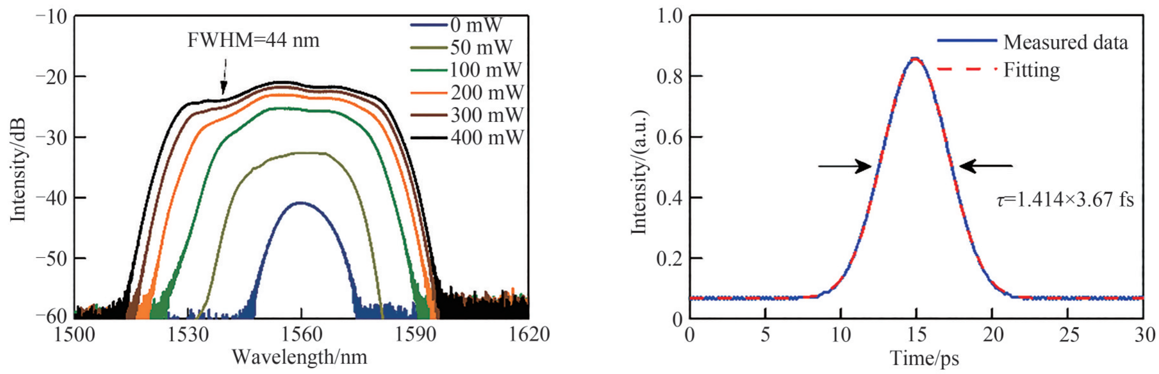
(a) Output spectrum of the oscillator　(b) The autocorrelation trace

(c) Oscilloscope trace of the oscillator　(d) RF spectrum

图3　色散管理型锁模光纤激光器的输出特性

Fig. 3　Output characteristics of dispersion-managed mode-locked fiber lasers

基于自相似放大理论，脉冲在正色散光纤中将由高斯型演化为抛物线型。同时由于SPM的作用，光谱宽度会随着泵浦功率的增加而增大。根据模拟仿真可知，光纤长度越长，所获得的脉冲光谱宽度越大。为了获得宽光谱抛物线脉冲，我们选择10 m长的正色散EDF作为预放大器，并通过调节泵浦功率大小改变输出脉冲的光谱大小及形状。不同泵浦功率下的输出光谱如图4(a)所示，随着泵浦功率的增大，光谱宽度单调增加，并且光谱也从高斯型演化为顶部平坦边沿陡峭的形状，这是抛物线脉冲的典型特征[21-25]。当泵浦光功率为400 mW时，光谱的半高全宽为44 nm，输出功率为87 mW，脉冲自相关迹如图4(b)所示，高斯拟合后脉宽为3.67 ps，此时的谱宽以及脉宽分别与图2(b)中的点 b 和 f 的值对应。

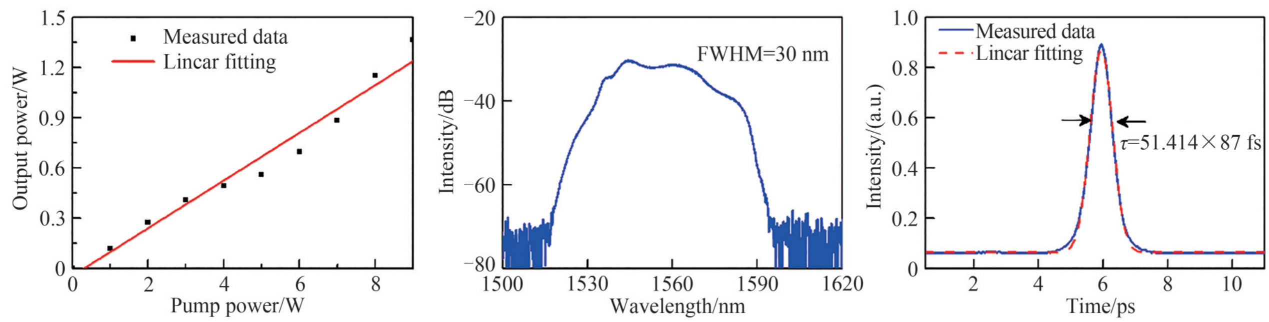


(a) The optical spectra at different pump powers (b) The autocorrelation trace

图 4　自相似放大后激光器输出特性

Fig. 4　Output characteristics of the laser after self-similar amplification

放大后的脉冲随后在 15 m 长的 DCF 中进行时域展宽以降低峰值功率。由于 DCF 和 SMF 之间的模场直径不匹配，输出功率将下降至 42 mW。接着脉冲将在 2.3 m 长的 DC-EYDF 中进行进一步放大，脉冲输出功率随泵浦光功率的变化如图 5(a)所示，当泵浦功率为 9 W 时测量的输出功率为 1.3 W。图 5(b)为放大后的光谱图，可以明显观察到由于放大器中的增益窄化效应，光谱带宽减小至 30 nm，对应于图 2(b)中的点 d。放大后的脉冲将通过准直器输出为空间光，并利用光栅对进行压缩。由于 DC-EYDF 的纤芯半径近似于单模光纤，因此不存在高阶模式[13]，通过红外激光显示卡观察到的输出光为高斯型圆斑，光束质量良好。为了测量压缩后的脉冲宽度，我们将自相关仪的光纤输入端口更换为空间光端口，并通过两块反射镜调整光束平行入射。图 5(c)为自相关仪测得的最窄压缩脉冲，高斯拟合后的脉宽为 587 fs。可以发现实验结果的脉宽大小是理论模拟的两倍，其主要原因是光栅对存在固有的高阶色散，将导致光纤展宽器无法与之完全匹配，出现色散失配现象从而影响脉冲宽度。此外，该激光器在长时间工作下具有良好的稳定性。



(a) Variation of output power with the pump power (b) Output spectrum of the main-amplifier (c) The autocorrelation trace

图 5　主放大器后的激光器输出特性及压缩时域

Fig. 5　Output characteristics of laser after main-amplifier and compressor

3　结论

本文研究了一种工作在 1.55 μm 附近的基于抛物线演化的宽光谱啁啾脉冲放大系统，搭建了碳纳米管锁模的色散管理型激光器，并将其作为种子源注入到正色散的 EDF 中实现自相似放大，以获得宽光谱高能量脉冲。随后脉冲经 DCF 展宽以降低峰值功率，并使用单模芯径的 Er/Yb 共掺光纤进一步放大。当主放大器的泵浦功率为 9 W 时，输出功率达 1.3 W，并最终利用光栅对将脉冲压缩至 587 fs，在 40.1 MHz 的重复频率下实现脉冲能量为 32 nJ，光谱宽度为 30 nm 的脉冲输出。本文所研究的激光器结构紧凑，简易方便，为光纤型宽光谱高能量激光器系统的实现提供了可行方案。

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Broadband Fiber Chirped-pulse Amplification System Based on Parabolic Evolution

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Abstract: Fiber lasers have attracted substantial research interest due to their high stability, excellent beam quality and system compactness. Furthermore, lasers generating high-energy ultrafast pulses and operating at the 1 550 nm region are widely developed due to the low optical attenuation at the first communication window and more cost-effective than other laser sources in a variety of applications such as ultrafast spectroscopy, precision material processing and terahertz-wave generation. To achieve high-energy pulses, an Erbium-doped fiber amplifier was employed to amplify seed pulses. However, pulses will accumulate large nonlinear effects such as Self-Phase Modulation (SPM) and Stimulated Raman Scattering (SRS) during direct amplification, thus degrading the pulse quality. One common solution is to widen the pulse width by introducing a chirp before amplification. The peak power intensity is significantly attenuated, avoiding excessive nonlinearity. The amplified pulse is then de-chirped by a compressor. This method is called Chirped Pulse Amplification (CPA). Several high-power CPA systems operating at 1.56 μm have been demonstrated in recent years. However, all of these sources produced a pulse with spectral width between 5 nm and 15 nm. Broadband fiber laser plays an important role in optical frequency combs, optical coherent tomography, optical coherence radar and fiber optical sensing systems. There is a lack of high-energy devices capable of generating pulses with spectral width above 30 nm. Several approaches have been utilized to generate broadband pulses. A noise-like mode-locked fiber laser was demonstrated based on the precise adjustment of intracavity dispersion. However, this laser regime was seldom applied in ultrashort pulses due to its incompressibility. A Mamyshev oscillator is able to generate broadband pulses as shorter than 100 fs at the expense of complicated intracavity structure and accurate pulse evolution. The extra-cavity generation method relies on Highly Nonlinear Fibers (HNLFs), such as photonic crystal fibers, whose complexity of design is increased by demanding careful selection of parameters for the seed pulse. In addition, the nonlinear effect induced by SPM generates a nonlinear chirp on both sides of pulses which degrades the beam quality in CPA systems. Note that self-similar pulses are nonlinear optical structures whose amplitudes and widths could be altered by dispersion, nonlinearity, gain and other system parameters, while maintaining the overall shapes. Since the self-similar pulse has a strict linear frequency chirp induced by the balance between SPM and normal group velocity dispersion in the erbium-doped fiber, it could be effectively compressed by grating pairs to obtain a high-power ultrashort pulse. Therefore, the combination of self-similar amplification and CPA is a promising solution to generating broadband watt-level pulse. High-energy ultrafast pulses based on parabolic evolution in ytterbium-doped lasers have been reported. Nevertheless, the Erbium-Doped Fiber Amplifier (EDFA) based on self-similar amplification operates at an anomalous dispersion region, which is less applicable to generating pulses with the average power above watt-level high-energy pulses comparing to Ytterbium-Doped Fiber Amplifier (YDFA). At the same time, high-energy CPA systems operating at 1 550 nm significantly lag behind Yb-doped lasers due to high quantum defect, thermal effects and nonlinearity. At present, there is no report on a broadband high-energy CPA system based on parabolic evolution operating at 1 550 nm. Here, we demonstrated an all-fiber Er-doped chirped-pulse amplification laser, which generates Watt-level broadband pulse with the application of self-similar amplification. Numerical simulations of the model laser were performed by following the propagation of the pulses and considering every action of cavity components on the pulses. We use the results of one round-trip circulation as the input of the next round of calculation until the optical field becomes self-consistent. For this context, pulse propagation equation is given by the nonlinear Schrodinger equation. The parameters of each element of the laser are optimized according to theoretical simulations. In our experiment, the seed source is a dispersion-managed passively mode-locked fiber laser with a Gaussian-spectral profile, which evolves into a parabolic shape after self-similar amplification, achieving a broadband pulse bandwidth with the full-width at a half-maximum of 44.8 nm under 400 mW pump power. The spectral width and energy of the pulse increase rapidly during amplification. The pulses are stretched in Dispersion Compensating Fiber (DCF) to reduce peak power, avoiding excessive nonlinearity. Then a Double-Clad Er/Yb co-Doped Fiber (DC-EYDF) is used as the main amplifier. The spectral width of the pulse is narrowed down to 30 nm with the effect of gain filtering during amplification. The pulse is amplified to 1.3 W with the pump power of 9 W. The amplifier delivers 32 nJ pulses at a repetition rate of 40.1 MHz, which can be compressed down to 587 fs through a pair of transmission gratings. We believe that the narrower pulses could be achieved by switching to fiber Bragg gratings to adjust the dispersion between the stretchers and compressors precisely. The robust, broadband, and watt-level 1 550 nm fiber laser source can be used for nonlinear frequency conversion, solar cell micromachining and ophthalmology due to its compact size.

Key words: Chirped-pulse amplification; Self-similar amplification; Broad spectrum; Erbium-doped fiber; Erbium-ytterbium co-doped fiber

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