基于宽带啁啾光纤光栅掺铒光纤激光啁啾脉冲放大方法研究

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摘要　报道了一种基于宽带啁啾光纤光栅作为展宽器和压缩器的飞秒全保偏掺铒光纤激光放大系统。该系统基于啁啾脉冲放大方法和色散补偿光纤对啁啾脉冲色散调制，并经过具有不同色散量的啁啾光纤光栅对的优化组合，最终实现了重复频率为 59.5 MHz、脉宽为 63 fs、峰值功率为 35.2 kW 的飞秒激光输出。

关键词　激光光学；光纤激光放大器；超短脉冲；全光纤；啁啾脉冲放大

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1 引　言

在过去几十年里，光纤激光器因散热性好、光-光转换效率高、光束质量好等突出优点发展迅速，在科学应用[1-5]、工业加工[6-10]、生物医学[11-15]等领域应用广泛。掺铒光纤激光器因工作波长为 1.5 μm，在光纤通信、环境监测、医疗设备等领域也有着广泛的应用。并且高功率飞秒掺铒光纤激光器可以输出很宽的相干光谱，使其可应用在精密光谱测量等领域。光纤激光级联放大器可实现更高能量的脉冲激光，但放大过程中产生的各种非线性效应比如四波混频、自相位调制以及群速度色散限制了高峰值功率脉冲激光的输出。为解决这个问题，研究人员提出了啁啾脉冲放大(CPA)方法[16]。该方法基于激光脉冲先展宽后压缩的顺序，有效避免了激光脉冲在增益光纤中激发的非线性效应造成的脉冲分裂等不良现象，大大提高了输出激光脉冲的峰值功率。1994 年，CPA 方法首次应用于锁模光纤激光放大器[17]，其锁模脉冲经 SMF-28 光纤展宽和体光栅压缩，最后实现脉宽为 440 fs、单脉冲能量为 1.4 nJ 的激光输出。

近年来，基于 CPA 方法实现锁模掺铒光纤激光放大的报道相继涌现。2013 年，Sobon 等[18]提出了一种基于石墨烯锁模光纤激光器作为种子源的 CPA 系统，采用两种不同的体光栅作为展宽器和压缩器，最终输出激光脉宽为 810 fs、平均功率为 1 W。2014 年，Peng 等[19]报道了一种掺铒啁啾脉冲放大系统，分别使用色散补偿光纤和单模光纤作为展宽器和压缩器，最后获得单脉冲能量为 11.3 nJ、脉宽为 170 fs 的激光脉冲输出。2016 年，李浪等[20]搭建了一种工作于 1.5 μm 的全光纤飞秒脉冲放大系统，经过普通单模光纤压缩脉冲宽度，获得了平均功率为 1.18 W、脉宽为 420 fs 的飞秒脉冲。2017 年，Ou 等[21]报道了一种全光纤掺铒激光放大系统，输出脉冲宽度仅为 47 fs，输出平均功率为 1.22 W。Lin 等[22]设计搭建了一种全光纤掺铒激光放大系统，采用大模场光纤作为压缩器，最终获得峰值功率为 77.5 kW、脉宽为 177 fs 的飞秒激光脉冲。同年，Elahi 等[23]报道了一种工作在 1.55 μm 的 CPA 系统，分别使用色散补偿光纤和体光栅作为展宽器和压缩器，输出激光脉宽为 175 fs、平均功率为 3.5 W。2020 年，Wei 等[24]提出了一种紧凑的全光纤啁啾脉冲放大系统，使用空芯光子晶体光纤作为压缩器，最终输出激光脉宽为 344 fs、平均功率为 1.02 W。

本文基于宽带啁啾光纤光栅和色散补偿光纤对

锁模激光群速度色散调制的全保偏掺铒光纤啁啾脉冲放大方法进行深入研究。整个系统由一个种子源和一个级联放大器组成。在激光放大过程中,采用宽带啁啾光纤布拉格光栅(CFBG)作为展宽器和压缩器,并通过保偏色散补偿光纤色散补偿优化,最终实现脉宽为 63 fs、单脉冲能量为 2.2 nJ 的线偏振激光输出。
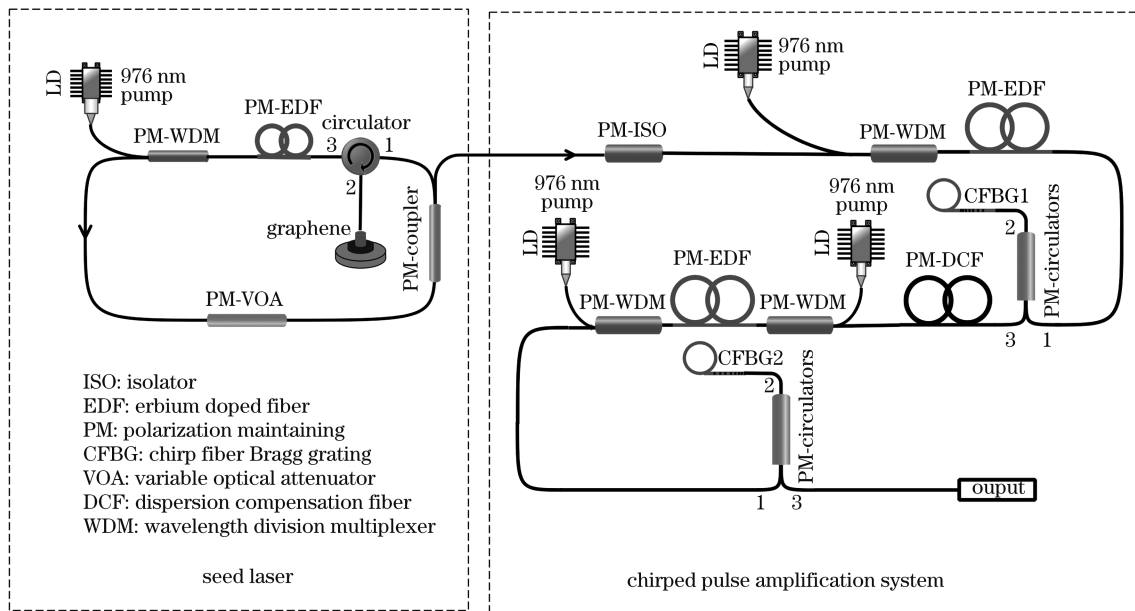
2 实验装置

2.1 脉冲种子源

锁模激光种子源如图 1 所示,由以下器件组成:

976 nm 泵浦源,保偏波分复用器,可调谐保偏光纤衰减器,30% 输出保偏光纤耦合器,保偏光纤环形器,石墨烯可饱和吸收镜,以及 1 m 保偏掺铒增益光纤(PM-ESF-7/125)。可调谐保偏光纤衰减器可连续调节腔内激光信号损耗,便于实现在中心波长 1550 nm 处稳定的锁模激光输出。振荡器的总腔长约为 3.4 m,腔内净色散约为 −0.07 ps²,其输出的激光是传统的负色散孤子,具有良好的自启动特性。同时,全保偏光纤结构能够保证整个谐振腔工作在高稳定锁模状态。

图 1 实验装置示意图

Fig. 1 Schematic diagram of experimental setup

ISO: isolator
EDF: erbium doped fiber
PM: polarization maintaining
CFBG: chirp fiber Bragg grating
VOA: variable optical attenuator
DCF: dispersion compensation fiber
WDM: wavelength division multiplexer

seed laser

chirped pulse amplification system

2.2 级联放大器

锁模激光放大系统由预放大级和主放大级两部分组成,如图 1 所示。预放大级经过保偏隔离器与种子源隔离,以保护锁模振荡器免受后端元件产生反射激光的影响。采用额定功率 650 mW 的 976 nm 泵浦源进行前向泵浦,1 m 掺铒光纤(PM-ESF-7/125)作为增益介质,实现锁模激光的初级放大。主放大级采用啁啾脉冲放大方法,首先预放大后的锁模脉冲经过 CFBG 展宽,再经过 5 m 保偏色散补偿光纤(DCF)对脉冲群速度色散进行微调,该 DCF 光纤单位长度群速度色散为 0.1275 ps²/m。为使增益光纤中铒离子得到充分储能,主放大级采用双向泵浦,其单个泵浦源的输出额定功率为 750 mW,其增益介质采用长度为 2.2 m 的掺铒光纤(PM-ESF-7/125)。最后,放大的激光脉冲被宽带啁啾光纤光栅压缩。

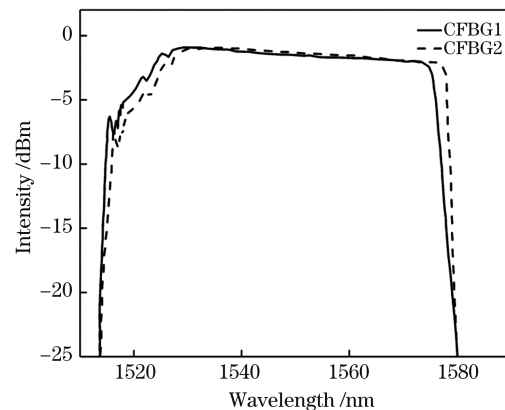本实验采用的宽带啁啾光纤光栅反射谱的中心波长为 1547 nm,谱宽约为 65 nm,如图 2 所示。两个 CFBG 的色散参量未知,其结构示意图如图 3 所

图 2 啁啾光纤光栅反射谱
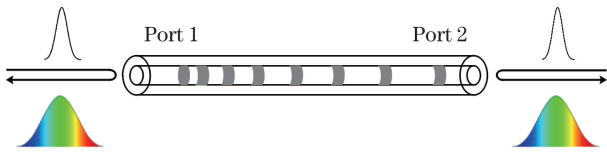
Fig. 2 Reflection spectrum of CFBG

图 3　啁啾光纤光栅结构特征示意图

Fig. 3　Structure diagram of chirped fiber Bragg grating

示。反射端口 Port1 和 Port2 可对多波长激光脉冲分别蓝移和红移,即对无色散激光脉冲实现负色散展宽和正色散展宽。另外,CFBG 可对激光正负色散脉冲起到反向调制作用。可使导入到 Port2 端口的负啁啾激光转变成正啁啾激光,从而获得正色散脉冲激光。这为激光脉冲色散调制提供了一种便利的方法。

所有实验数据的采集基于以下测量仪器:光谱仪(Yokogawa AQ6375,分辨率 0.02 nm),7.5 GHz 频谱分析仪(Keysight EXA N9010A,带宽 7.5 GHz),示波器(LeCroy,带宽 1.0 GHz),自相关仪(Femtochrome,FR-103XL)和光功率计(NewPort 2936-c)。

3　实验结果及分析

本实验所使用的种子源是自行搭建的基于石墨烯可饱和吸收镜锁模的掺饵光纤激光环形谐振腔。当泵浦功率为 140 mW 时,通过精调腔内损耗,获得稳定的锁模激光输出。种子源输出激光脉宽为 480 fs,谱宽为 6.5 nm,平均功率为 4.8 mW,重复频率为 59.5 MHz,频谱的信噪比(SNR)大于 65 dBm,如图 4 所示。种子源输出的时间带宽积为 0.388,接近理论极限值 0.315。预放大后的激光脉宽为 500 fs,其脉冲和光谱特征如图 5 所示。经过预放大后,激光脉冲的平均功率被放大到 40 mW,是种子源脉冲能量的近8倍。预放大后的激光脉冲能量可
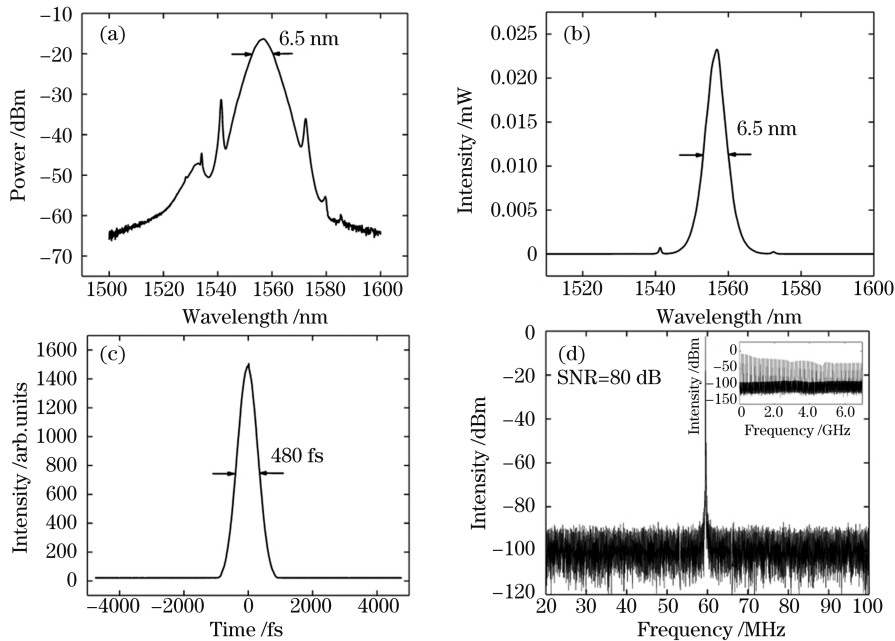

图 4　种子激光器的特性。(a)光谱;(b)线性光谱;(c)自相关曲线;(d)频谱

Fig. 4　Characteristics of seed laser. (a) Optical spectrum; (b) linear optical spectrum; (c) autocorrelation curve; (d) frequency spectrum
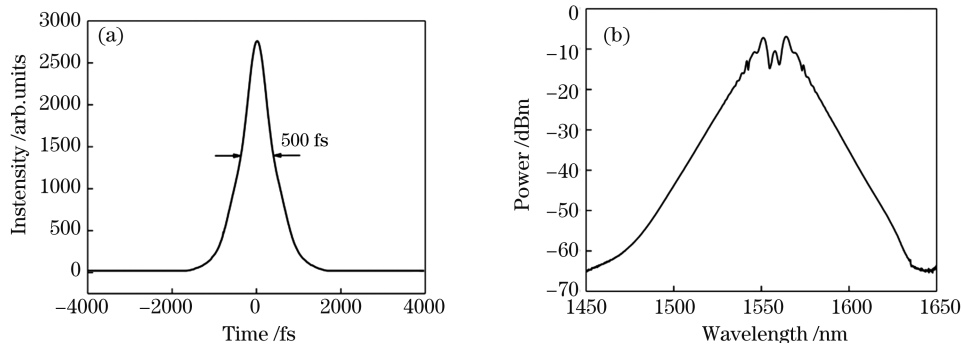

图 5　预放大后的激光特性。(a)自相关曲线;(b)光谱

Fig. 5　Characteristics of pre-amplifier laser. (a) Autocorrelation curve; (b) optical spectrum

为主放级双向泵浦增益光纤高储能提供足够强的抽运能力,有效弥补了种子源输出激光脉冲能量不足。

在主放大级中,基于 CFBG 的两个反射端口 Port1 和 Port2 先后对预放大输出激光进行正负色散脉冲展宽,并利用色散补偿光纤对激光脉冲群速度色散进行优化补偿。其中,负色散脉冲展宽即激光脉冲经过 CFBG 蓝移反射端 Port1 展宽,短波激光在脉冲前沿;正色散脉冲展宽即激光脉冲经过 CFBG 红移反射端 Port 2 展宽,长波激光在脉冲前沿。经展宽的激光脉宽约为 24 ps,为原激光脉冲宽度近 50 倍。最后,再经另一 CFBG 的相反色散端口对放大后的激光脉冲进行压缩。研究发现,激光脉冲经过 CFBG1 的 Port1 展宽,再经前后总泵浦功率为 900 mW 储能的增益光纤放大后,经 CFBG2 的 Port2 压缩,获得平均功率为 110 mW、峰值功率为 1.6 kW、脉宽为 1.107 ps 的激光脉冲,其脉冲特征如图 6(a)所示。接着,采用 CFBG1 Port 2 红移反射端对预放大输出激光展宽,经同样泵浦功率储能的增益光纤放大后,再经 CFBG2 Port 1 蓝移反射端对激光脉冲压缩,获得平均功率为 132 mW、峰值功率为 35.2 kW、脉宽为 63 fs 的超短激光脉冲,其脉冲特征如图 6(b)所示,其光谱特征如图 6(c)所示。
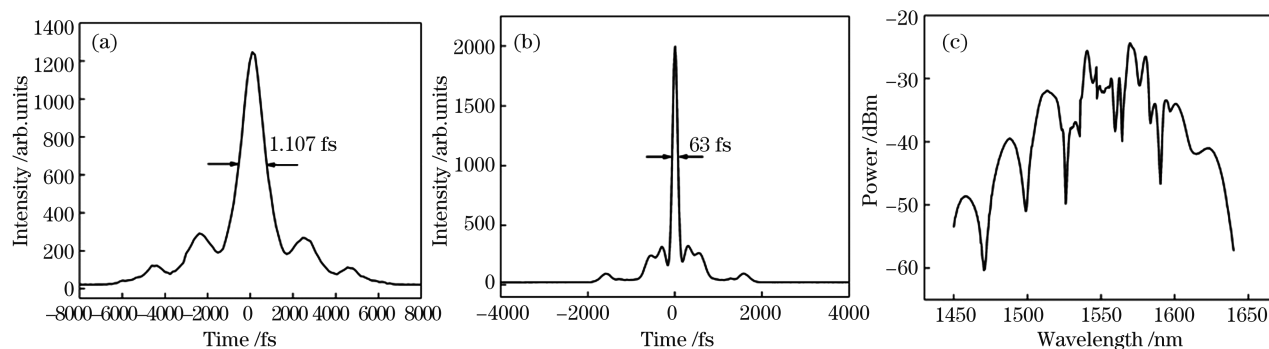

图 6 主放级输出激光特性。(a)自相关曲线;(b)展宽后的自相关曲线;(c)光谱

Fig. 6 Characteristics of main-amplifier output laser. (a) Autocorrelation curve; (b) widened autocorrelation curve; (c) optical spectrum

以上两个明显不同的输出激光脉冲宽度基于两种可能因素:1)根据传统啁啾脉冲放大,正色散脉冲激光更易于压缩而实现超窄脉宽,在本实验中由脉冲激光在 CFBG 压缩过程中激发的自相位调制非线性效应的差异造成的;2)两个光纤光栅色散系数的差异在啁啾脉冲放大中同时起到了补偿部分啁啾脉冲群速度色散的作用。为了验证第一种可能因素,本文对 CFBG1 的蓝移端口 Port1 展宽和 CFBG2 的红移端口 Port2 压缩这种方案进行微调。在不改变光纤光栅原反射端口接入的情况下,调换两个 CFBG 的前后位置,即基于 CFBG2 的红移反射端口 Port2 对预放大激光脉冲先进行展宽,同样泵浦条件下对信号光放大,最后利用 CFBG1 的蓝移端口 Port1 对激光脉冲压缩。结果发现,光纤光栅前后调换后的啁啾脉冲放大激光脉冲特征几乎没有变化。这说明基于 CFBG 的正色散啁啾脉冲放大压缩效果与负色散啁啾脉冲放大压缩效果没有区别,第一种可能因素并不成立。因此,两个不同的激光脉冲输出结果可完全归因于 CFBG1 和 CFBG2 具有不同的群速度色散参量。

为了分析色散参量不同的两个 CFBG 在啁啾脉冲放大过程中起到补偿群速度色散的优化组合,假定 CFBG1 和 CFBG2 在该实验装置中对激光脉冲产生的色散量分别为 φ_1 和 φ_2,并假定本装置中种子源和两级放大中增益光纤和传能光纤对脉冲激光产生的群速度总负色散量为 $-\varphi$,其部分色散被色散补偿光纤产生的群速度正色散 φ_3 补偿。经过 CFBG1 的 Port2 红移端口展宽和 CFBG2 的 Port1 蓝移端口压缩的放大激光脉冲群速度色散可表示为 $-\varphi+\varphi_1-\varphi_2+\varphi_3$。根据该公式,只有在 $\varphi_1>\varphi_2$ 情况下,两个光纤光栅对激光脉冲产生正色散差,可补偿激光装置中的负色散,实现脉宽 63 fs 的超短脉冲输出。反之,如果采用 CFBG1 的 Port1 蓝移端口展宽和 CFBG2 的 Port2 红移端口压缩,则输出激光脉冲群速度色散为 $-\varphi-\varphi_1+\varphi_2+\varphi_3$,两个光纤光栅的色散差 $-\varphi_1+\varphi_2$ 为负,不利于脉冲群速度色散补偿,故获得 1.107 ps 较宽的激光脉冲输出。在本实验中,经 CFBG1 的 Port2 红移端口展宽和 CFBG2 的 Port1 蓝移端口压缩的啁啾脉冲放大方法能够更好地补偿整个光纤光路中的群速度色散,获得 1.223 ps 较窄脉宽脉冲,再利用 5 m DCF 光纤补偿部分群速度负色散,获得 63 fs 超短激光脉冲。

4 结 论

本文搭建了一个稳定的全光纤化的飞秒保偏激光放大系统，由锁模光纤激光源和两级放大器组成，采用两个色散量不同的 CFBG 分别作为脉冲展宽器和压缩器，最终获得平均功率为 132 mW、峰值功率为 35.2 kW、脉宽为 63 fs 的超短脉冲激光输出。并定性分析了两个 CFBG 群速度色散差量在啁啾脉冲放大中对实现超短脉冲起到的关键作用。这种具有线偏振特性的飞秒光纤激光系统作为一种高稳定超快脉冲源，在科学研究和工业通信等领域具有广阔的应用前景。

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Research on Erbium-Doped Fiber Lasers Using Chirped Pulse Amplification Method Based on Broadband Chirped Fiber Grating

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Abstract

Objective   Fiber lasers have been widely used in scientific research, industrial processing, biomedical, and other fields because they offer unique characteristics such as good heat dissipation, high light-light conversion efficiency, and excellent beam quality. As a classic fiber laser, the erbium-doped fiber laser with a wavelength of 1.5 μm has been widely used in optical fiber communication, environmental monitoring, medical facility, precision spectroscopy, and other fields. Cascade amplification is a typical technique for achieving high-power pulsed lasers, but group velocity dispersion and the damage threshold of fiber materials attributed to nonlinear effects such as four-wave mixing and self-phase modulation, restrict the high-power ultrashort pulse output. To overcome this limitation, chirped pulse amplification has been proposed. The laser pulse is first stretched temporally, amplified, and compressed again. This method can effectively suppress phenomena such as self-focusing and pulse splitting caused by nonlinear effects and improve the peak power of laser pulse. In this study, a femtosecond laser amplification system based on all-polarization-maintaining erbium-doped fibers using broadband chirped fiber gratings was reported. Using chirped pulse amplification and group velocity dispersion optimization that combines dispersion compensation fibers with the chirped fiber grating pair with different dispersions, a femtosecond laser pulse with pulse width, peak power, and repetition rate of 63 fs, 35.2 kW, and 59.5 MHz, respectively, was experimentally obtained.

Methods   The amplification system (Fig.1) proposed herein was divided into two parts, namely, the seed laser and two-stage cascade amplifier. First, an erbium-doped ring fiber laser mode-locked using a graphene saturable absorber was established. Then, the two-stage amplifier was connected to the back of the seed laser and a polarization-maintaining isolator was inserted between the two amplifiers. After preamplification using the first-stage amplifier with a forward pump, the preamplified pulse was stretched using the broadband chirped fiber Bragg grating (CFBG). Next, the group velocity dispersion was compensated for by using the polarization-maintaining dispersion compensation fiber. Subsequently, it was amplified using the main amplifier with a bidirectional pump. The amplified laser pulse was further compressed using another broadband CFBG. Subsequently, we qualitatively analyzed the main influence of the group velocity dispersion difference of the two CFBGs on realizing the high-power ultrashort pulse output.

Results and Discussions　For seed laser, the laser was pumped with a 976 nm laser with 140 mW average power. The measured pulse width, spectral bandwidth, and average power of the seed laser output were 480 fs, 6.5 nm, and 4.8 mW, respectively. The time-bandwidth product was calculated to be 0.388, which is close to the Fourier transform limit. Moreover, the fundamental repetition rate with respect to the signal-to-noise ratio of 65 dB was measured to be 59.5 MHz (Fig. 4). For preamplified laser, the pulse width was 500 fs (Fig. 5). In the main amplifier stage, CFBG was used to expand the preamplified output laser pulse and the group velocity dispersion in the system was optimized using the dispersion compensation fiber. Finally, the amplified laser pulse was compressed by splicing the opposite port of another CFBG. The study found that the laser pulse was broadened by splicing Port 1 of CFBG 1, amplified using 2.2 m gain fiber with a total pump power of 900 mW, and compressed by splicing Port 2 of CFBG 2, a laser output with an average power, peak power, and pulse width of 110 mW, 1.6 kW, and 1.107 ps, respectively, were obtained (Fig. 6). Then, using the method in which the amplified lase pulse was broadened using CFBG 1 Port 2, amplified using the gain fiber with the same pump power, and compressed using CFBG 2 Port 1, ultrashort laser pulses with an average power, peak power, and pulse width of 132 mW, 35.2 kW, and 63 fs, respectively, were obtained (Fig. 6). Using analysis, the results of the above two laser pulse outputs were attributed to the difference in the group velocity dispersion parameter between CFBGs 1 and 2.

Conclusions　Herein, a stable femtosecond laser amplification system based on all-polarization-maintaining erbium-doped fibers was established. The system comprised a mode-locked fiber laser source and two-stage amplifier. Two CFBGs with different dispersion parameters were used as a pulse stretcher and compressor for chirped pulse amplification. Finally, an ultrashort pulse laser output with an average power, peak power, and pulse width of 132 mW, 35.2 kW, and 63 fs, was realized. The key role of the group velocity dispersion difference between the two CFBGs in the chirped pulse amplification of the ultrashort pulse output was qualitatively analyzed. As a highly stable ultrafast pulse source, the femtosecond fiber laser system with linear polarization characteristics shows potential applications in scientific research, communication engineering, etc.

Key words　laser optics; fiber laser amplifier; ultrashort pulse; all-fiber; chirped pulse amplification

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