中国激光

高功率超快光纤激光技术发展研究

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摘要　自 1960 年第一台红宝石激光器问世以来，高速更新换代的固体激光器、光纤激光器、气体激光器和半导体激光器为通信、工业加工与制造、军事国防、前沿科学研究等领域的研究和发展提供了有力的支撑。其中，光纤激光器以其良好的散热特性、出色的激光模式、更高的放大效率、更为紧凑的空间结构和更加低廉的制作成本成为新一代高功率超快激光研发的首选。得益于光纤的波导特性和大比表面积的散热特点，光纤激光器可以在高平均功率状态下实现高光束质量的长期稳定工作。结合啁啾脉冲放大与多通道相干合束的办法，目前高功率超快光纤激光器已经实现了万瓦级平均功率、百飞秒级脉冲宽度的高功率超快激光输出。本文面向高功率超快光纤激光系统，介绍高功率超快光纤激光研究发展现状，协同阐述超快光纤振荡器、光学参量管理、超快光纤放大器和非线性压缩四部分的原理和内在联系，并对高功率超快光纤激光的未来发展方向做出展望。

关键词　激光光学；高功率激光；超快激光；光纤激光；非线性管理；相位管理

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1　引　　言

光纤激光器的概念由美国 Optical 公司的 Snitzer 研究员首次提出。1961 年，Snitzer[1]在掺钕玻璃波导中观察到激光现象（被认为是世界上第一台光纤激光器）。1964 年，Koester 等[2]利用掺钕玻璃光纤实现了激光放大。受限于泵浦源功率与光纤传输损耗，他们只获得了百毫瓦级的输出功率。1966 年，Kao 等[3]在经过大量理论计算之后，得出石英光纤损耗可以降低到 20 dB/km 的结论，并获得了 2009 年诺贝尔物理学奖。1978 年，贝尔实验室 Stolen 等[4]在光纤中发现了自相位调制（SPM）现象，利用这一现象可以有效展宽脉冲激光光谱宽度。1984 年，贝尔实验室的 Tomlinson 等[5]通过模拟，从理论上验证了 SPM 现象对激光脉冲光谱展宽的可行性，为后续预啁啾管理放大技术（PCMA）、非线性压缩技术等提供理论依据。1985 年，为抑制非线性效应和高峰值功率脉冲引起的光学损伤问题，Strickland 等[6]提出了啁啾脉冲放大（CPA）技术，该技术通过展宽信号光脉冲宽度，对脉冲激光放大过程中峰值功率进行抑制，实现线性放大过程，大幅度提高了超快激光器的脉冲能量和输出功率。并首次在实验上获得了脉冲能量 1 mJ、脉冲宽度 2 ps、脉冲峰值功率 500 MW 的超快激光输出。啁啾脉冲放大技术对高功率超快激光发展具有重要价值，获得了 2018 年的诺贝尔物理学奖。在 1988 年，Snitzer 等[7]首次报道了双包层光纤，分别利用内包层与纤芯传输泵浦光与信号光，有效解决了高功率多模泵浦光的耦合问题。在保证输出光的输出模式下，双包层增益光纤的应用有效提高了 CPA 光纤放大器的输出功率。1997 年，Taverner 等[8]提出了大模场光纤的概念，他们将掺铒单模光纤的纤芯直径

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增加至 14～17 μm，使得光纤模场面积达到了 200～300 μm^2，从而降低了脉冲光在光纤中的功率密度，进而大幅度提升了光纤中的非线性效应阈值，实现了 158 μJ 的单脉冲能量。在上述理论研究与实验技术基础上，新型的放大技术不断涌现和发展，主要包括分脉冲放大（DPA）、多通道相干合束放大、预啁啾管理放大、相干脉冲堆积（CPS）等。基于上述放大技术，目前已实现平均功率万瓦级、脉冲能量百毫焦级、脉冲宽度数个飞秒的超快激光输出。图 1 为高功率超快光纤激光发展史。

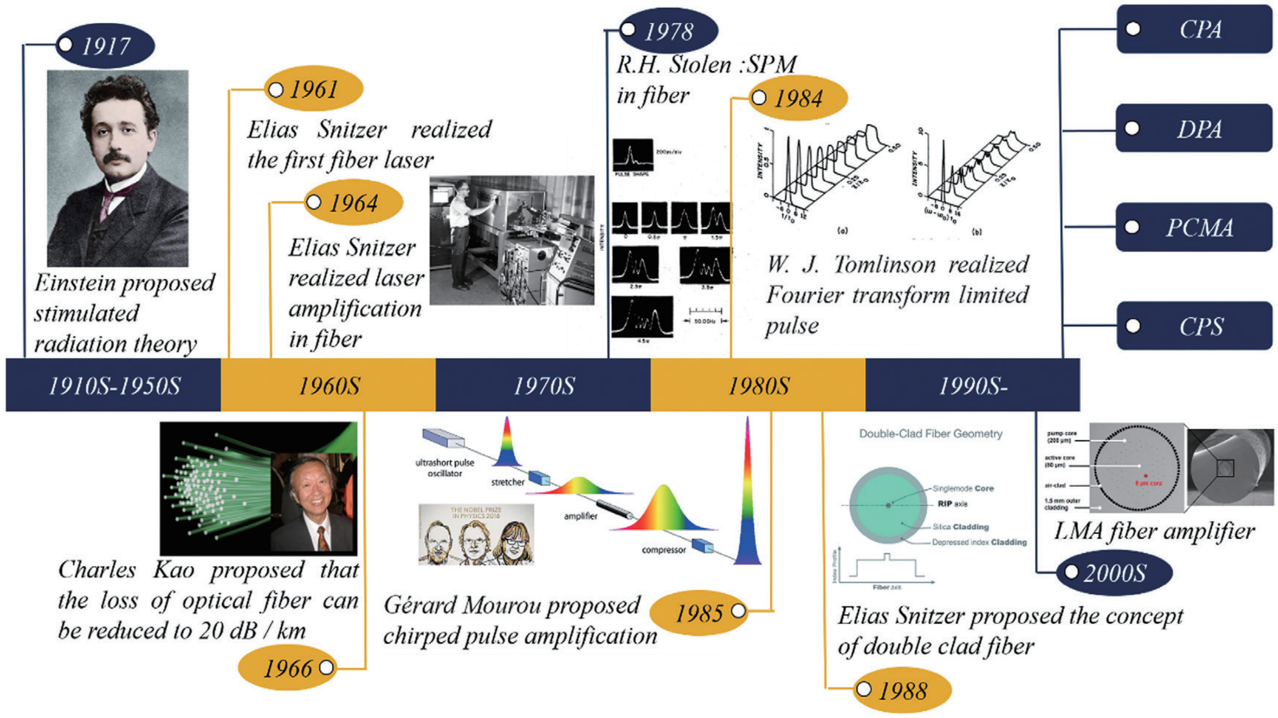


图 1　高功率超快光纤激光发展史

Fig. 1　Development history of high power ultrafast fiber laser

高功率超快激光器已成为精密加工、前端科学研究、天文探测等高精尖领域的重要工具。在精密加工方面，基于高功率超快激光器的激光加工设备能在极短的时间内将大量能量施加于微小区域内，实现无材料选择性、无重铸层、无微裂纹、无再结晶的高精度加工，已成为包括航空航天装备制造在内的高端制造业的重要发展方向。在前端科学研究方面，基于超快激光的高速探测系统，已成为观测超晶格量子阱材料中载流子的行为、有机偶极分子的光致电荷转移及电荷分离行为等微观动力学过程、血红蛋白动力学、DNA 能量转移的过程等生物化学基本过程的有力工具；同时，高功率超快激光在新型相干光源产生过程中具有重要应用，超快激光具有极高的峰值功率，易诱发非线性效应，目前已成为实现极紫外（XUV）相干光源与阿秒脉冲的重要能量源；基于超快飞秒激光技术的光整流效应法和光电导天线法可产生 THz 波[9]。在天文探测方面，基于超快光纤激光的光学频率梳频谱覆盖范围广、频率分辨率高、稳定性良好、光谱标定精度高，成为天文探测及天体物理等科学领域研究的有力工具[10]。

本文针对高功率超快光纤激光的研究进展，阐述包括超快光纤振荡器、光学参量管理、超快光纤放大器以及非线性压缩四部分的原理和发展现状，并对高功率超快光纤激光的未来发展方向做出展望。

2　超快光纤振荡器

基于被动锁模技术[11-12]搭建的超快光纤振荡器是实现高功率超快激光的基础。被动锁模光纤激光器主要由增益介质、锁模部件、色散延迟线和非线性部件组成，如图 2 所示。常见的光纤激光被动锁模技术可分为半导体可饱和吸收镜（SESAM）锁模、非线性偏振旋转（NPR）锁模、非线性环路反射镜（NLM）锁模[13-15]。基于光克尔效应，上述被动锁模技术通过控制脉冲在光纤激光环形腔内的非线性相位，实现基于增益竞争过程的纵模相位锁定，完成被动锁模过程。

图 3 为目前基于被动锁模激光技术的光纤激光振荡器研究成果分布图[16-49]，横坐标为脉冲重复频

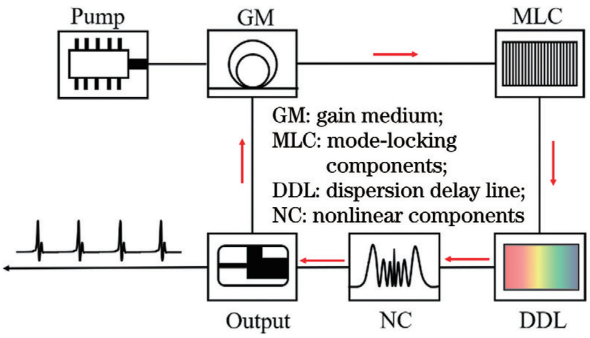


图 2　被动锁模光纤激光器结构示意图

Fig. 2　Structure diagram of passive mode-locked fiber laser

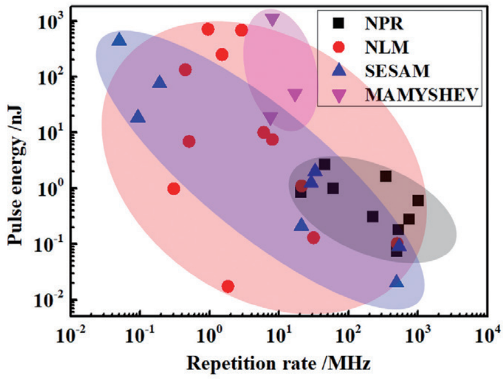


图 3　基于被动锁模技术的光纤激光振荡器研究成果分布图[16-49]

Fig. 3　Distribution of research results of passively mode locked fiber laser oscillators[16-49]

率，纵坐标为单脉冲能量。从图中可见，基于 NPR 技术的锁模光纤激光重复频率主要分布在 1 MHz～1 GHz，脉冲能量主要为 nJ 量级。NPR 锁模激光器结构简单，自启动特性良好，可以实现高功率、高重频的超短脉冲激光输出。采用 NPR 锁模方式，Li 等[16]报道了重复频率 1 GHz 的 1 μm 锁模光纤激光器，输出激光的脉冲宽度为 64 fs、平均输出功率最高可达 600 mW，此结果是基于 NPR 锁模实现的最高重复频率，可以应用于光学频率梳、脉冲堆积和基于腔增强的高次谐波产生等。由于非线性偏振旋转过程只能发生在单模光纤中，因此基于 NPR 锁模技术的光纤激光对外在环境较为敏感，温度、湿度以及光纤应力变化都会破坏锁模激光的稳定运行。

基于 NLM 锁模技术的光纤激光重复频率主要分布在 100 kHz～1 GHz，脉冲能量最大可达到 μJ 量级；NLM 基于干涉原理实现快饱和吸收体的功能。因此，NLM 锁模光纤激光器能够实现全保偏光纤结构，具有良好的环境稳定性。2019 年，Dou 等[36]报道了基于 NLM 锁模技术的全光纤激光器，输出的中心波长在 1940.8 nm，最大平均功率为 1.98 W，单脉冲能量为 684 nJ，这是目前利用 NLM 锁模技术所能获得的最高平均输出功率和单脉冲能量。基于 NLM 锁模技术的光纤激光器需要较长的环内单模光纤来提供足够的非线性相移差，因此该类锁模激光器难以实现高重复频率脉冲激光输出。而且，受 NLM 锁模物理机制的影响，锁模激光存在自启动困难的问题，需要通过施加外界应力刺激等方法辅助实现锁模激光脉冲的建立。

基于 SESAM 技术的锁模光纤激光重复频率主要分布在 10 kHz～1 GHz，脉冲能量可达到亚 μJ 量级。该类锁模光纤激光器具有低锁模阈值、光学结构简单、自启动性能良好和可直接实现高脉冲能量输出的优点。2019 年，Swiderski 等[48]利用 SESAM 实现了中心波长位于 2 μm 的 440 nJ 的单脉冲能量的光纤激光输出。受 SESAM 材料响应速度和自身反射带宽的限制，基于 SESAM 锁模技术的脉冲激光很难实现飞秒级的宽光谱锁模脉冲。同时，为满足 SESAM 材料饱和光强的要求，腔内激光需经过透镜变换聚焦至 SESAM，存在高功率密度情况下器件损伤的问题。因此，长期工作稳定性一直是困扰 SESAM 锁模激光发展与应用的一个重要问题。

Mamyshev 锁模光纤激光器[50-52]作为近几年提出的基于非线性光谱展宽锁模技术的新型锁模光纤激光器，重复频率主要分布在 10 MHz，脉冲能量为 μJ 量级，如图 3 所示。Mamyshev 锁模激光器在实现宽光谱、高脉冲能量的超短脉冲方面具有极高的应用价值。2019 年，Liu 等[49]使用掺镱的大模场光子晶体光纤搭建 Mamyshev 振荡器，实现脉冲能量 1.125 μJ、重复频率 8 MHz、峰值功率约 13 MW 的脉冲激光输出。2021 年，首先提出 Mamyshev 锁模激光器结构的 Wise 课题组实现了脉冲能量 21 nJ，重复频率 16.8 MHz，脉冲宽度 65 fs 的 Mamyshev 锁模光纤激光器，并对环形腔内脉冲演化动力学进行了详细的理论分析[53]。一般情况下，Mamyshev 锁模激光器需要主动调制或外部种子来实现腔内锁模过程，相信随着非线性光学理论与光纤激光锁模理论的应用和发展，Mamyshev 锁模激光器能够解决自启动的问题以满足更大范围的应用需求。

除以上几种锁模激光器外，基于二维材料可饱和吸收体的锁模光纤激光器受益于二维材料本身优

良的宽带可饱和吸收特性和超短的可饱和恢复时间，可以实现短脉宽、高重复频率和高稳定型光纤激光输出[54]。2012 年，Martinez 等[55]搭建了基于石墨烯锁模的 Er、Yb 共掺光纤超快激光器，实现了基频重复频率 9.67 GHz、脉冲宽度 865 fs 的超高重复频率超短脉冲输出。2017 年，Liu 等[56]搭建了基于 NPR 与二维材料 WS_2 的混合锁模光纤激光器，在中心波长 1540 nm 处实现了 67 fs 的超快激光输出。随着新型二维材料的不断涌现，此类锁模光纤激光器有了更多发展的可能[57-58]。然而二维材料目前现存的制备工艺难以实现对材料结构的精细控制，而且二维材料的长期稳定性也有待进一步研究。如何提高二维材料对氧化、水解等环境因素的耐受能力，以及如何实现其非饱和损耗、调制深度和可饱和恢复时间的优化设计是未来二维材料锁模激光发展的重要方向。

超快光纤锁模激光器是发展高功率超快光纤激光的核心模块。面对日益增长的高平均功率和短脉冲宽度等超短脉冲光学参数的要求，如何协同整个高功率超快激光系统的设计，实现光学系统各模块间的光学参量管理是实现高质量、高功率超短脉冲光纤激光输出的关键。

3 光学参量管理

在高功率超快光纤激光系统中，光学参量管理是实现高质量、高功率超短脉冲激光输出的关键技术。在这一节中，我们所提光学参量管理包括色散管理、光谱管理和脉冲整形。其中，基于色散管理的光学啁啾脉冲放大过程能够在协同大功率放大的情况下，通过展宽器与压缩器的色散共轭管理，实现高质量的超短脉冲输出；光谱管理通过对光频分量的强度抑制，实现对光谱构型的调制，从而优化压缩器对高功率超短脉冲的压缩质量；同样，脉冲整形通过对强啁啾脉冲的波形进行调制，实现对应超短脉冲光谱构型的调制和优化，协助实现高质量的超短脉冲压缩。

3.1 色散管理

在高功率超快激光系统中，利用色散元器件对激光脉冲的二阶和三阶色散进行共轭调控，实现激光系统展宽与压缩过程中超短脉冲的色散管理，如图 4 所示，$\varphi_S^{(2)}$、$\varphi_A^{(2)}$、$\varphi_C^{(2)}$、$\varphi_S^{(3)}$、$\varphi_A^{(3)}$、$\varphi_C^{(3)}$ 分别为展宽器、放大器、压缩器提供的二阶色散和三阶色散。脉冲展宽过程可以通过展宽器引入足量的脉冲啁啾，实现对信号光脉冲的展宽。常见的脉冲展宽器件有：色散补偿光纤（DCF）、啁啾布拉格光栅（CBG）和 Öffner 型光栅等[59-63]。脉冲压缩是通过色散共轭补偿前置系统引入的脉冲啁啾，实现近傅里叶变换极限的脉冲压缩。常见的脉冲压缩器件有：光栅对、棱镜光栅和啁啾镜[64-66]。在上述展宽与压缩器件中，光栅对所能提供的色散量较高，可以作为展宽器和压缩器，实现 fs 脉冲的展宽和压缩，在 CPA 系统中最为常用。

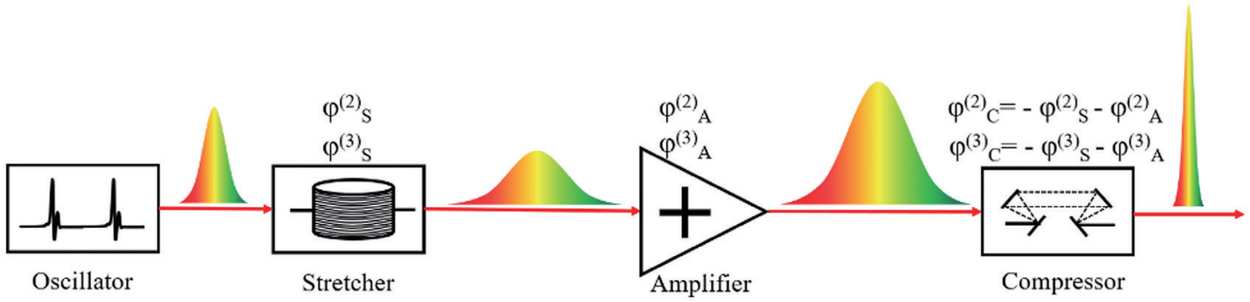


图 4 高功率超快激光系统图

Fig. 4 Diagram of high power ultrafast laser system

色散管理需要通过匹配展宽器与放大器和压缩器的色散参数来实现。常见的展宽器和压缩器的组合有光纤布拉格光栅展宽器和 Treacy 型光栅压缩器[67-68]，Öffner 型光栅展宽器和 Treacy 型光栅压缩器[69-70]，基于色散补偿光纤的全光纤展宽器和光栅压缩器[71]，以及全光纤展宽器和 grism 压缩器[72]等。其中，对窄光谱超短脉冲放大而言，光纤布拉格光栅可以通过光学设计实现与 Treacy 型光栅对压缩器的色散共轭补偿，实现高质量的脉冲放大压缩过程；对于宽光谱超短脉冲，由于光纤布拉格光栅存在反射带宽限制，基于 DCF 的全光纤展宽器成为高功率超快激光系统中与光栅对进行色散共轭补偿的首要选择。2020 年 Niu 等[68]在 CPA 光纤放大器中，通过设计色散共轭匹配实现了高质量脉冲压缩，利用色散可调啁啾光纤布拉格光栅（CFBG）展宽脉冲，之后利用 Treacy 型光栅对展宽放大后的脉冲进

行压缩，最终得到的脉冲能量为 10 μJ，脉冲宽度为 250 fs，接近傅里叶变换极限，最终输出的脉冲如图 5 所示。

2019 年，Liu 等[71]搭建了基于 CPA 结构的 1 μm 全光纤高功率超快激光器，实现重复频 1 MHz、脉冲宽度 245 fs、脉冲能量>55 μJ 的高功率超短脉冲输出。利用 DCF 结合四通展宽结构将种子源脉冲展宽至 800 ps，最终利用光栅对压缩器实现脉冲宽度 245 fs 的近傅里叶变换极限的脉冲压缩。结果如图 6 所示，脉冲在经过色散管理后实现了良好的线性放大，所积累的 B 积分参数约为 6 rad。

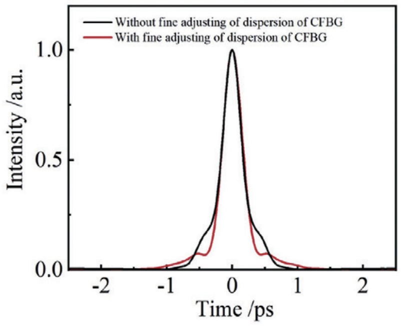


图 5　在 10 μJ 脉冲能量下，测量得到的 CFBG 色散微调前后压缩脉冲的自相关轨迹[68]

Fig. 5　Measured autocorrelation trace of the compressed pulses with and without fine adjusting of dispersion of CFBG at 10 μJ pulse energy[68]

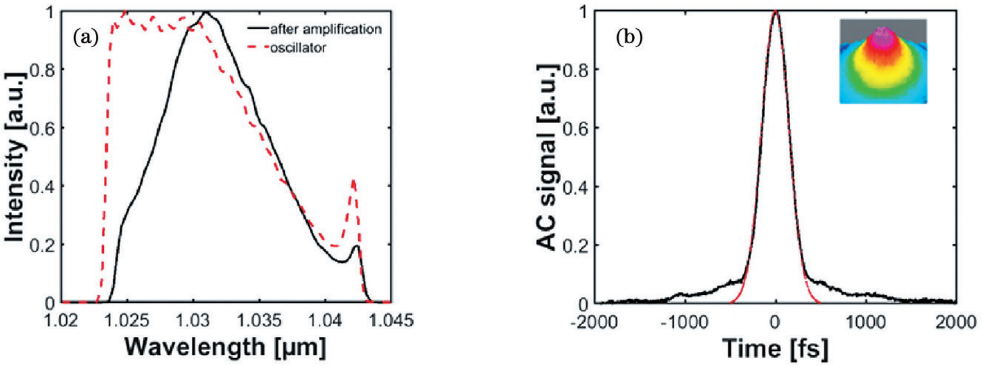


图 6　实验结果。(a)放大器输出的脉冲光谱；(b)放大器输出的脉冲自相关轨迹(插图：输出光斑形状)[71]

Fig. 6　Experimental results. (a) Pulse spectrum at the output of the amplifier; (b) autocorrelation trace of the amplifier pulses (inset: output beam profile)[71]

3.2　光谱管理及脉冲整形

在高功率超快激光系统中，高阶相位的积累会引起脉冲时域波形畸变，降低脉冲质量。这些积累的高阶相位与超短脉冲光谱相位的非线性项有关，常用 B 积分量化表示[73]。对具有高斯光谱构型的超短脉冲而言，当 B 积分>π rad 时，积累的非线性相位会对光谱相位曲线的平坦性造成影响，导致难以通过常规色散管理器件实现高质量、高功率超短脉冲的展宽和压缩；对具有抛物线光谱构型的超短脉冲，残余非线性相位的累积不会破坏光谱相位曲线的平坦性，因而可以通过常规色散管理器件实现高质量的脉冲压缩。

2007 年，Schimpf 等[74]研究了高功率超快激光中不同光谱构型对脉冲压缩质量的影响。通过空间光调制器将光谱整形为高斯型和抛物线型，比较 B 积分在 3.5 rad(存在低非线性)和 16 rad(存在高非线性)情况下，两种光谱对应的时域脉冲压缩情况。如图 7(c)所示，具有高斯型光谱构型的超短脉冲在 B 积分达到 16 rad 的情况下，其光谱相位的平坦性相较于 3.5 rad 遭到了破坏，因而很难实现高质量的脉冲压缩；如图 7(d)所示，对具有抛物线构型光谱的超短脉冲而言，在 B 积分达到 16 rad 的情况下光谱相位仍然可以保持平坦性，从而可以利用光栅对实现高质量的脉冲压缩。具有抛物线构型的超短脉冲除了通过昂贵的空间光调制器获得以外，还可以利用自相似放大过程实现。协同长增益光纤中增益窄化效应、正色散和非线性相位，可以实现具有抛物线构型光谱的脉冲输出[75-76]。

与光谱管理原理相仿，脉冲整形通过对超短脉冲时域波形的调制，来改变其光谱构型和光谱相位曲线。通过光谱相位曲线的平坦化设计，实现高质量的超短脉冲压缩。2020 年，Mueller 等[77]协同啁啾脉冲放大和相干合成技术，实现了平均功率 10.4 kW 的高功率超快激光输出。基于脉冲整形，得到如图 8(b)插图所示的矩形脉冲，经压缩后最终得到的输出脉冲宽度为 254 fs，接近傅里叶变换极限。

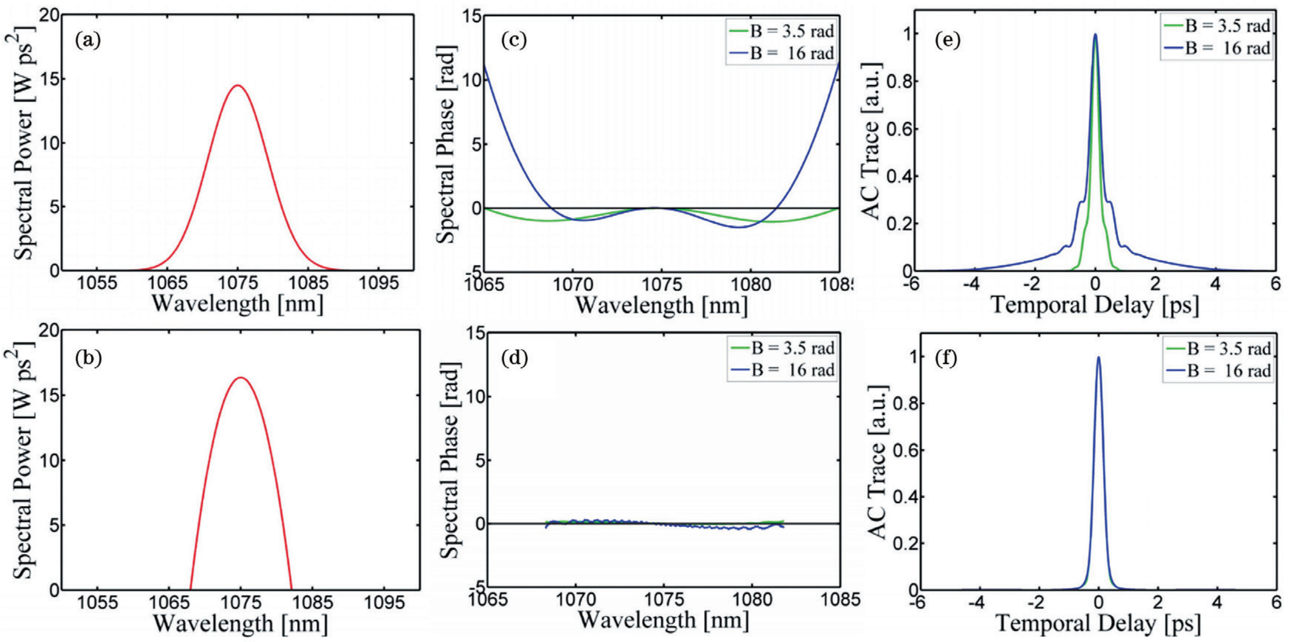


图 7 实验模拟结果。(a)高斯型光谱;(b)抛物线型光谱;(c)高斯型光谱与(d)抛物线型光谱在 B 积分为 3.5 rad 和 16 rad 下的相位曲线;(e)高斯型光谱与(f)抛物线型光谱在 B 积分为 3.5 rad 和 16 rad 时对应的脉冲自相关轨迹[74]

Fig. 7 Experimental simulation results. (a) Gaussian spectrum; (b) parabolic spectrum; phase-profiles of (c) Gaussian spectrum and (d) parabolic spectrum at power levels corresponding to B-integrals of 3.5 rad and 16 rad, respectively; corresponding autocorrelation traces of (e) Gaussian spectrum and (f) parabolic spectrum at power levels corresponding to B-integrals of 3.5 rad and 16 rad, respectively[74]

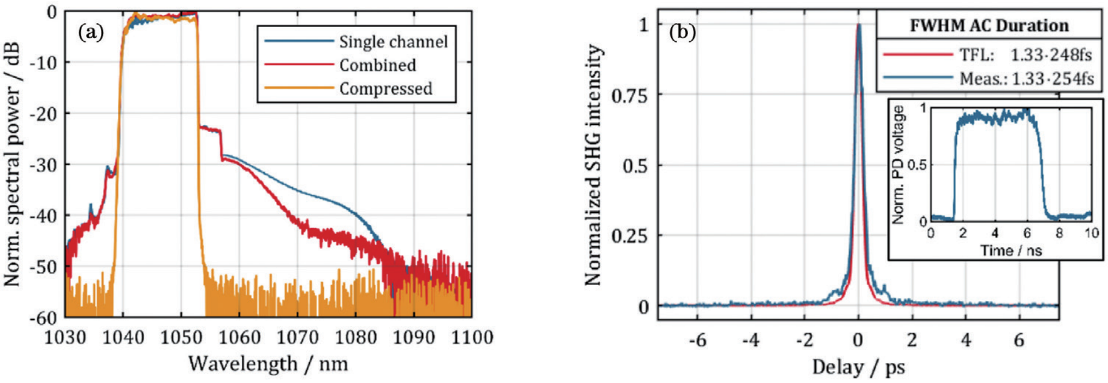


图 8 高功率超快激光输出。(a)压缩前单通道和压缩前后组合光束的全功率光谱;(b)测量的脉冲和计算得到的变换极限(TFL)非共线强度自相关轨迹(插图:主放大器输出展宽脉冲形状)[77]

Fig. 8 High-power ultra-fast laser output. (a) Full power spectrum of single channel before compression and combined beam before and after compression; (b) measured and calculated transform-limited (TFL) non-collinear intensity autocorrelation (inset: output stretched pulse shape of the main amplifier)[77]

4 超快光纤放大器

高功率超快激光光纤放大器是实现高功率超快光纤激光输出的核心器件。如何合理地设计放大器结构,避免横模不稳定性、自聚焦效应和高功率密度导致的热畸变/热损伤,是困扰着高功率超快光纤激光放大器发展的主要问题。目前常用光纤激光放大技术有:CPA[6]、DPA[78]、PCMA[79]。协同系统色散管理、光谱管理和脉冲整形,结合上述光纤放大技术实现有效相位管理的超短脉冲放大过程,是保障实现高质量的高功率超短脉冲输出的关键。

图 9(a)为 CPA 技术原理图。利用展宽器在信号光脉冲中引入大量啁啾,在功率放大之前实现脉冲的充分展宽,极大程度上降低脉冲的峰值功率,从而抑制放大过程中的非线性效应,避免由自聚焦效应导致的器件光损伤。经历展宽和线性放大过程的

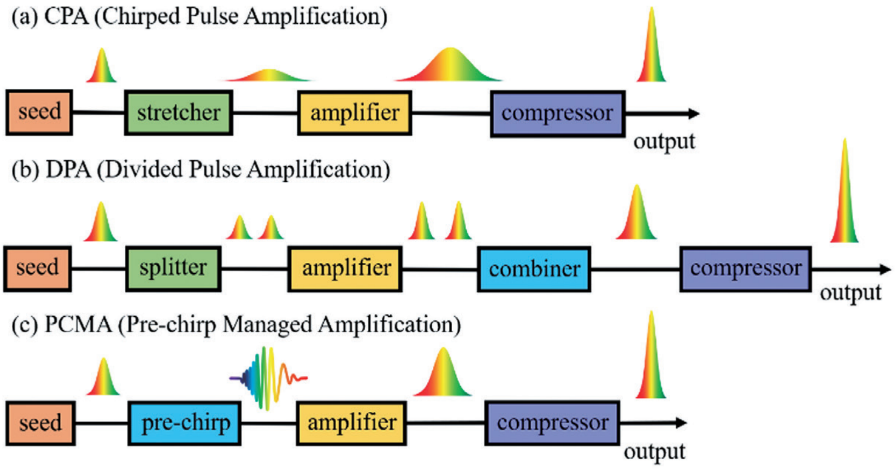


图 9　放大技术原理图。(a)啁啾脉冲放大;(b)分脉冲放大;(c)预啁啾管理放大

Fig. 9　Schematic diagram of amplification technology. (a) Chirped pulse amplification; (b) divided pulse amplification; (c) pre-chirp managed amplification

高功率信号光脉冲可以利用常规压缩器件实现高质量的脉冲压缩。目前基于单通道 CPA 的高功率光纤激光可实现平均功率 830 W、脉冲宽度 640 fs、重复频率 78 MHz[80] 的脉冲激光输出。利用受限掺杂的大芯径双包层增益光纤作为放大器增益介质可以一定程度上抑制其横模不稳定性问题,但是受限于目前所能获得的大芯径增益光纤的光学性质,高功率光纤 CPA 系统的平均输出功率难以实现进一步的提升[81]。与 CPA 技术思路相仿,在充分抑制放大过程非线性效应的基础上,为实现更高功率的超快激光输出,提出了 DPA 技术[78],如图 9(b)所示。通过分光器将单个信号光脉冲分裂成数个低峰值功率的子脉冲,所有子脉冲在经过放大后利用合束器将子脉冲重新合成为一个高功率的信号光脉冲,从而实现放大功率的成倍提升。利用 DPA 技术,Limpert 等取得了突出的成果。先后研发了 2 通道[82-83]、4 通道[84-85]、8 通道[70,86]、12 通道[77] 和 16 通道[87-88] 的分脉冲放大系统。其中 2020 年报道的 12 通道的光纤激光放大器通过分束、放大、合束等过程实现了平均功率万瓦级的突破,最终输出的超快光纤激光平均功率达到了 10.4 kW,脉冲宽度为 254 fs[77],如图 10 所示。

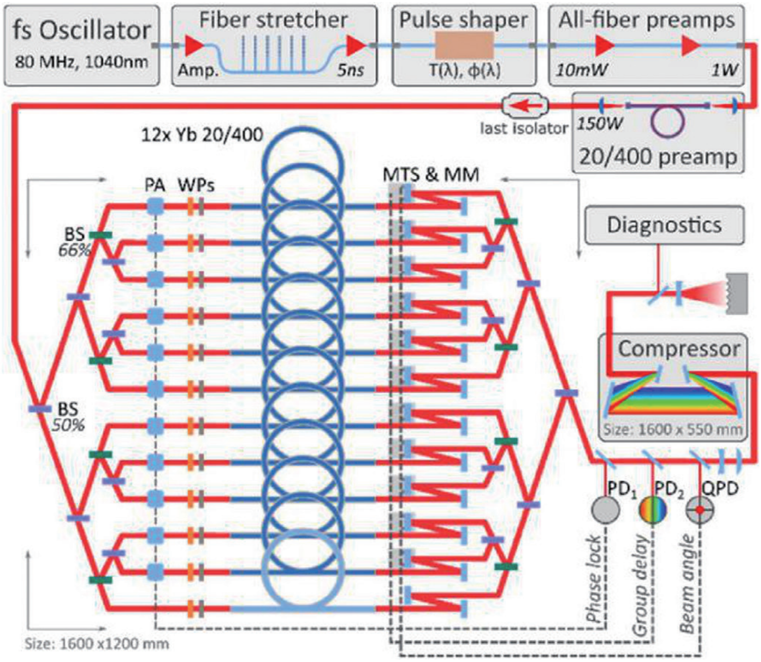


图 10　10.4 kW 光纤激光系统结构图[77]

Fig. 10　Schematic construction of the 10.4 kW fiber laser system [77]

受增益光纤增益窄化效应的影响，基于 CPA 与 DPA 技术实现的高功率超快光纤激光器很难实现亚百飞秒级脉冲宽度的直接激光输出。针对强场物理、显微成像等对激光脉冲宽度有着较高要求的应用，需要级联非线性光谱展宽与脉冲压缩级。采取这样的方法虽然可以实现高脉冲能量的少光周期超短脉冲输出，但是由于光学系统结构复杂程度的提升，高功率光纤激光系统的稳定性显著下降。针对这一问题，PCMA 因其系统结构复杂程度较低，无需级联非线性压缩级便可实现少光周期的超短脉冲输出，近年来得到了普遍的重视和广泛的发展[89]。如图 9(c)所示，PCMA 通过在信号光脉冲中引入适量的负啁啾，从而使脉冲宽度的最小值产生在正色散光纤放大器中，并引入较强的自相位调制效应对信号光光谱实现非线性展宽。由于自相位调制效应引入了线性上啁啾，所以放大后的高功率脉冲能够在级联的压缩器中直接实现少光周期的高质量脉冲压缩，避免了引入非线性光谱展宽与脉冲压缩级。PCMA 所能实现的脉冲最高峰值功率受自聚焦效应(4 MW)的影响，目前只能实现微焦级脉冲能量，更进一步的能量放大需要寻求新的非线性超短脉冲放大技术。为避免 DPA 技术中偏振分割引起的偏振和时间延迟，利用 CPS 的方法，把现有的脉冲列看作已经分割好的脉冲，然后利用腔增强技术，直接将脉冲列中一定数量的脉冲在腔内叠加在一起，也能够实现大能量激光输出。

图 11 为近几年基于 CPA、DPA、PCMA 和 CPS 技术所实现高功率超快激光输出参数的统计和整理。CPA 技术可以实现脉冲能量毫焦量级、平均功率亚千瓦级的高功率超快激光输出。协同 DPA 技术与 CPA 技术实现的高功率超快激光，输出脉冲能量可达数十毫焦级，平均功率为万瓦量级。利用 PCMA 技术可以直接获得脉冲能量微焦量级，脉冲宽度数十飞秒的高功率超短脉冲激光输出，避免了使用非线性光谱展宽和脉冲压缩模块。利用 CPS 技术，可以实现毫焦量级的大能量超快脉冲激光输出，并且有效避免了偏振分割对脉冲产生的一系列影响。

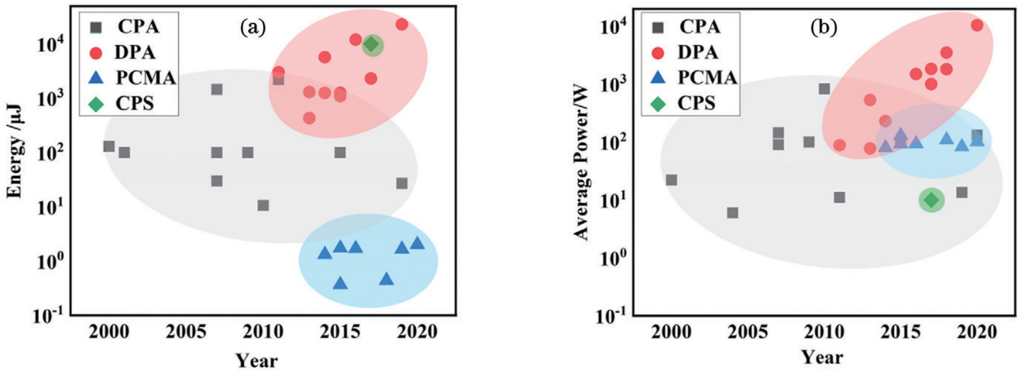


图 11　近几年基于 CPA、DPA、PCMA 和 CPS 技术所实现高功率超快激光输出参数。(a)1 μm 高功率超快激光年份-能量分布图；(b)1 μm 高功率超快激光年份-平均功率图[80，82-88，90-112]

Fig. 11　In recent years, high-power ultra-fast laser output parameters based on CPA, DPA, PCMA, and CPS technologies have been achieved. (a) Year-energy distribution diagram of 1 μm high-power ultrafast laser; (b) year-average power distribution diagram of 1 μm high-power ultrafast laser[80, 82-88, 90-112]

4.1　CPA 技术发展现状

CPA 技术最初由 Strickland 等[6]提出，并于 2018 年获得诺贝尔物理学奖。通过使用色散管理元件引入足量线性啁啾，利用大芯径增益光纤为增益介质实现功率放大，利用光栅对实现脉冲色散补偿，是目前最为常用的实现高功率超快激光器的有效途径。

2010 年，Eidam 等[80]报道了具有最高平均输出功率的基于大芯径增益光纤的 CPA 光纤激光系统，如图 12 所示。通过 Öffner 型光栅展宽器将 200 fs 的种子源锁模脉冲展宽至 800 ps；分别使用长度为 1.2 m 和 1.5 m，模场直径为 30 μm 的双包层大模场增益光纤实现输出功率为 50 W 的功率预放大；使用长度为 8 m、模场直径为 27 μm 的双包层大芯径增益光纤进行功率放大，最终实现重复频率 78 MHz、平均功率 830 W、脉冲宽度 640 fs 的高功率超快激光输出。

CPA 技术也被应用于高功率掺铒和掺铥光纤放大器。2014 年 Peng 等[113]报道了一种 1550 nm CPA 系统。利用 CFBG 展宽器，采用长度 28 cm、模场直径 27 μm的掺铒大模场双包层增益光纤对

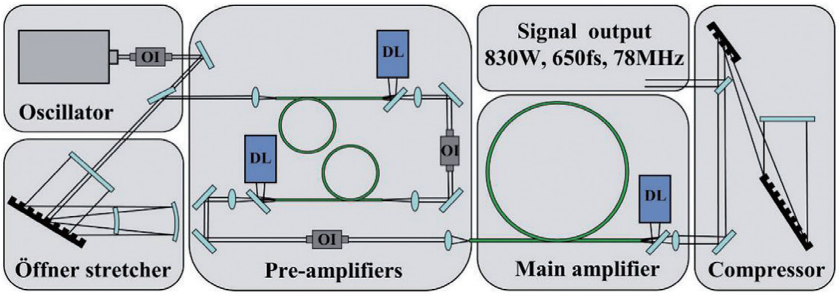


图 12　平均输出功率为 830 W 的 CPA 系统结构图[80]

Fig. 12　Structure diagram of CPA system with average output power of 830 W[80]

脉冲进行功率放大，采用光栅对压缩器对放大后的脉冲进行压缩。最终实现平均功率 4.4 W、重复频率 4.8 kHz、脉冲能量为 913 μJ、脉冲宽度<500 fs 的 1550 nm 脉冲输出。2016 年 Gaida 等[114]报道了一种采用掺铥的大模场光子晶体光纤作为增益介质的高功率 CPA 系统，利用 Öffner 型展宽器将脉冲展宽，使用掺铥光子晶体光纤对脉冲进行三级放大，实现平均功率 28.7 W、脉冲宽度 200 fs、重复频率 61 kHz 的近傅里叶变换极限的高功率脉冲输出。2018 年，Gaida 等[115]利用 50 μm 芯径的双包层保偏掺铥光子晶体光纤，实现平均功率>1 kW、脉冲宽度 265 fs、重复频率 80 MHz 的 2 μm 高功率超快激光输出，这是目前所能实现的 2 μm 波段最高的平均功率输出。

4.2　DPA 技术

DPA 技术由康奈尔大学应用物理系的 Zhou 等[78]在 2007 年提出，如图 13 所示。种子源脉冲经过 PBS 起偏器变为线偏光；经过由光轴垂直交错分布的双折射晶体组成的分束器，分裂为偶数个小脉冲；这一组小脉冲经过放大后，由法拉第晶体实现偏振态旋转 90°然后进行第二次放大；再次通过分束器时，由于该组放大后的小脉冲偏振态整体旋转 90°，所以此时的分束器可以作为合束器将小脉冲进行合束，合束后的高能量脉冲以 S 偏振态通过 PBS 输出，实现了 nJ 级脉冲能量、300 fs 脉冲宽度的分脉冲放大激光输出。

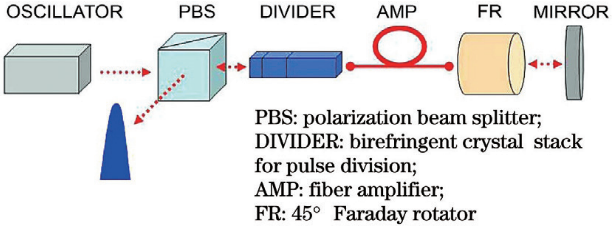


图 13　DPA 系统实验装置图[78]

Fig. 13　Experimental setup of DPA system[78]

除利用双折射晶体实现分脉冲放大原理外，还可以采用偏振控制和强度控制的办法，分别利用偏振分光棱镜和非偏振分光棱镜实现。2020 年，Mueller 等[77]在单通道 CPA 的基础上，通过 12 路单通道大芯径增益光纤放大器相干合束的办法，实现了平均功率 10.4 kW、脉冲宽度 254 fs 的高功率超快激光输出。输出脉冲宽度接近傅里叶变换极限，具有较高的光束质量（$M^2 \leqslant 1.2$），在 1 Hz～1 MHz 的频率范围内具有较低的相对强度噪声（0.56%）。

此外，基于分脉冲实现超短脉冲峰值功率抑制的方法也可以应用于基于惰性气体填充的非线性压缩模块。当空芯光纤所能承受的峰值功率达到上限时，可以利用分脉冲的方法，协同高峰值功率和非线性光谱展宽过程，实现高峰值功率的非线性脉冲压缩[116]。

4.3　PCMA 技术

PCMA 是基于自相位调制效应的非线性放大过程。通过对信号光脉冲进行预负啁啾处理，实现信号光峰值功率的放大和脉冲宽度的非线性展宽，经压缩后得到脉冲宽度为几十飞秒的超短脉冲，从而避免使用非线性压缩模块对放大后的信号光脉冲做进一步的处理。2016 年 Liu 等[117]报道了一种基于圆偏光放大的 PCMA 系统，实现了脉冲能量 4.2 μJ、脉冲宽度 36 fs 的超短脉冲输出，实验装置如图 14 所示。利用光栅对压缩器对 mini-CPA 结构输出的信号光脉冲进行线性预啁啾；啁啾后的脉冲经过四分之一波片变为圆偏光；利用长度 0.8 m、芯径 85 μm 的掺镱棒状光子晶体光纤对圆偏振信号光进行功率放大，最终通过光栅对压缩器对放大后圆偏振脉冲进行压缩，得到了平均功率 100 W、重复频率 23.7 MHz 的高功率超快激光。

虽然基于 PCMA 技术可以实现 μJ 级脉冲能量、少光周期脉冲宽度的高功率超快激光，但是受自

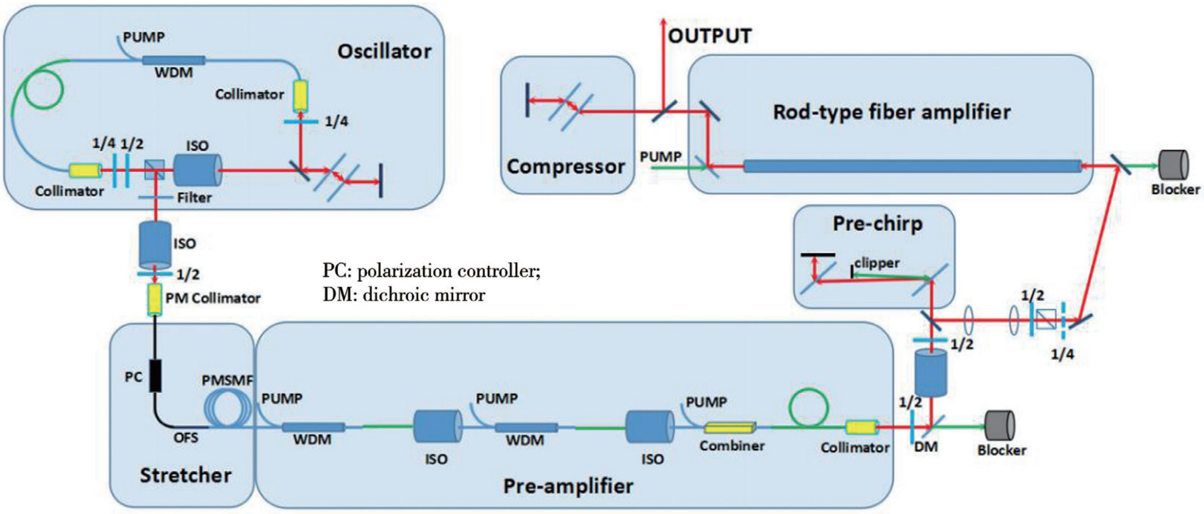


图 14　大功率 Yb 光纤 PCMA 系统结构示意图[117]

Fig. 14　Schematic construction of the high power Yb-fiber PCMA system[117]

聚焦效应的限制，脉冲能量(4 μJ@1 ps)很难实现进一步的放大。协同 DPA 与 PCMA 技术，可以实现非线性脉冲相干叠加放大的过程，在保证少光周期脉冲宽度的同时，实现数十微焦量级的脉冲能量放大。

4.4　相干脉冲堆积技术

相较于固体激光[118]所能实现的脉冲能量等级，现有放大技术的光纤激光由于自身物理条件的限制，很难实现焦耳级的脉冲能量放大。密歇根大学超快光学科学中心的 Zhou 等[119]提出了 CPS 的方法，为实现基于光纤激光放大器的大能量超短脉冲提供了一条新的途径。2017 年，Pei 等[112]报道了协同 CPS 技术和光纤 CPA 技术的大能量超短脉冲激光系统，如图 15 所示。通过将脉冲进行 81 次相干堆积，实现了脉冲能量 10 mJ、脉冲宽度约 540 fs 的大能量超短脉冲输出。

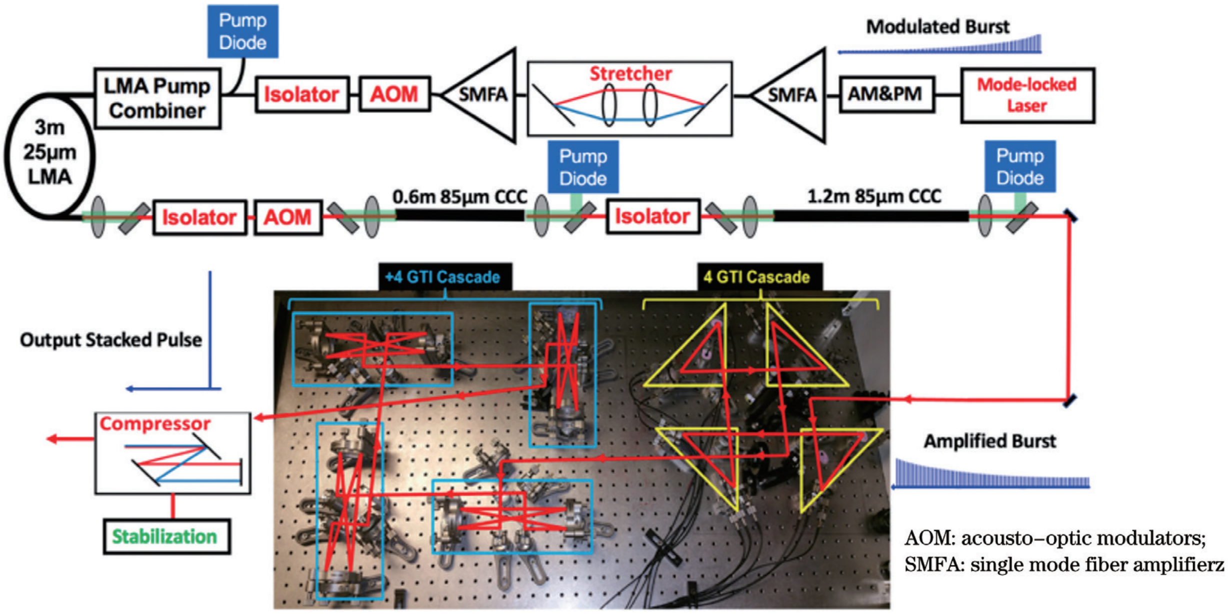


图 15　输出脉冲能量为 10 mJ 的 CPS 系统实验装置图[112]

Fig. 15　Experimental setup of CPS system with output pulse energy of 10 mJ [112]

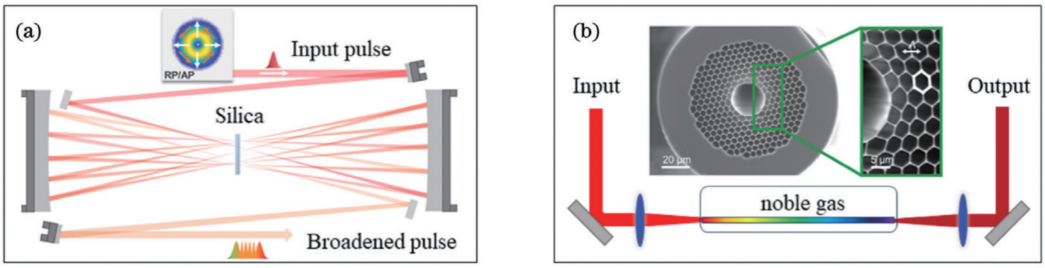
利用 CPS 技术虽然能够实现大脉冲能量的超短脉冲，但是脉冲相干堆积的光学系统结构复杂程度过高、系统稳定性受环境影响显著，需要高精度光束指向反馈控制系统稳定光路，难以通过进一步的脉冲堆积结构实现脉冲能量的提高。

5　非线性压缩

脉冲宽度为单个或少光周期的高功率超快激光已成为微观粒子动力学、光与物质作用、强场电子激发等前沿物理研究的重要工具[120-121]，目前主要依靠协同CPA技术和非线性压缩技术实现。利用介质的自相位调制效应实现对高功率脉冲激光的非线性光谱展宽，通过色散管理器件(啁啾镜)消除非线性展宽过程引入的脉冲啁啾，将脉冲宽度压缩至近傅里叶变换极限。目前已利用这一技术最高实现太瓦级峰值功率[120]、百毫焦级单脉冲能量[120]、单个光周期脉冲宽度的高功率超短脉冲[121]。

光波在介质中传播过程中会产生相位变化，这一变化取决于传播距离、材料折射率与光波长。对于具有高斯分布的超快激光脉冲而言，由于材料的克尔效应，材料的折射率随着光强波动发生变化，从而形成了与光强分布相关的相位变化。这种变化会形成新的光频分量，从而导致脉冲在频域上被充分展宽。通常而言，脉冲展宽效果与初始脉冲波形相关，对于高能量超短脉冲，频谱展宽能达到100 THz。

常见的非线性压缩器件有基于石英薄片的多通腔和惰性气体填充的空芯光纤。多通腔组成结构如图16(a)所示，腔镜由两片镀高反膜的凹面镜组成，石英薄片位于凹面镜焦点位置[122]，这一器件的工作阈值取决于凹面镜膜系的损伤阈值与石英薄片的损伤阈值，可满足百微焦级脉冲能量的超短脉冲非线性压缩需求[123]。2020年，Vicentini等[124]级联基于0.95 mm石英片的31通腔与17通腔，对脉冲宽度460 fs、脉冲能量20.5 μJ、中心波长1.03 μm的超快激光进行了非线性展宽，经啁啾镜压缩后实现了脉冲宽度22 fs、脉冲能量15.6 μJ的超快脉冲。针对具有更高脉冲能量超快激光的非线性压缩，需要使用惰性气体填充的空芯光纤作为非线性介质，结构如图16(b)所示[125]。与石英薄片相比，惰性气体的非线性折射率较低，入射脉冲宽度通常为数皮秒或亚皮秒级别，需要较长的空芯光纤，非线性光谱展宽过程存在较高的光谱能量损耗。2009年，Chen等[126]利用氖气填充的空芯光纤(2.5 m)对脉冲宽度22 fs、单脉冲能量2.5 mJ、中心波长780 nm的高能量短脉冲进行非线性压缩，最终实现脉冲宽度4.3 fs(1.6个光周期)、脉冲能量1 mJ的脉冲输出。



Multipass cell with thin plate　　Gas-filled hollow-core fiber

图16　常见的非线性压缩器件。(a)含石英片的多通池[122]；(b)惰性气体填充的多通池[125]

Fig. 16　Common nonlinear compression devices. (a) Multipass cell with quartz sheet; (b) multipass cell filled with noble gas

基于上述非线性压缩技术，针对石英薄片损伤阈值较低的问题，2021年，Kaumanns等[127]利用氩气填充替代石英薄片的办法，使用40通的多通腔结构实现对脉冲能量112 mJ、脉冲宽度1.3 ps、中心波长1.03 μm的超快脉冲的非线性展宽。最终获得压缩后单脉冲能量107 mJ，脉冲宽度37 fs的超短脉冲输出。同样针对非线性压缩系统脉冲能量损伤阈值的问题，2013年，Guichard等[128]提出了分脉冲非线性压缩方案，将脉冲激光分束、非线性展宽、合束、压缩，最终实现了脉冲宽度71 fs、脉冲能量7.5 μJ、中心波长1.03 μm的超短脉冲输出。

6　总结与展望

在过去的20年间，受益于大芯径增益光纤及棒状光子晶体增益光纤的问世，高功率超快激光得到了飞速的发展。基于CPA技术和多通道分脉冲相干合成技术，目前国际上高功率超快光纤激光器已分别实现平均功率10.4 kW和脉冲能量23 mJ的百飞秒级脉冲激光输出。然而，面对各类前沿应用对高功率超短脉冲激光所提出的越来越高的参数要求，光纤激光作为高功率超快激光发展的一个重要方向，在未来的发展中仍需面对以下关键问题。

需要通过寻找新的增益介质、发展现有放大技

术或寻求新的放大结构，来不断实现激光脉冲参数新的量级突破。新增益介质材料的寻找，需要综合考虑自聚焦效应、材料热损伤阈值和高阶非线性效应等因素。近年来新发现的单晶光纤以其相较于石英光纤更好的光学特性获得了广泛的关注，其中，基于 Yb∶YAG 的单晶光纤已经实现了平均功率 270 W 的飞秒脉冲单通道放大[129]。但如何有效实现长单晶增益光纤的制备和加工，成为了困扰基于单晶增益光纤的高功率超快光纤激光发展的主要问题。

多通道啁啾脉冲相干合束放大和相干脉冲堆积是目前实现大脉冲能量超短脉冲的有效途径。但是，更多通道数的相干合束和更多级次信号脉冲的堆积过程会严重影响光学系统的机械稳定性，对光束指向稳定系统提出了极为苛刻的要求。如何合理优化多通道相干合束结构和脉冲堆积过程，提高系统稳定性，成为实现更高功率超短脉冲光纤激光输出的重要问题。

协同增益介质的非线性光学特性和激光脉冲的光学演化特性。以新的视角看待脉冲与增益介质间的相互作用，提出能够同时实现大脉冲能量、超短脉冲宽度、超高平均功率等脉冲参数新的量级的光纤激光放大新方法是未来高功率超快光纤激光发展的趋势。相信随着光纤激光增益介质和超快光纤激光放大技术的迭代发展，高功率超快光纤激光器必然能在各个应用领域发挥更加重要的作用。

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Development of High-Power Ultrafast Fiber Laser Technology

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Abstract

Significance In 1960, after the invention of the first ruby laser, fast-developed solid-state, fiber, gas, and semiconductor lasers provided great support for the research and development of multiple applications, such as optical communication, industrial processing and manufacturing, military and national defense, and state-of-the-art scientific research. Fiber lasers with good heat dissipation characteristics, excellent transverse mode, high amplification efficiency, compact laser construction, and less costs have become the first choice in developing next generation high-power ultrafast lasers. Fiber lasers can achieve long-term operation stability with good beam quality under above-average power because of their waveguide characteristics and large specific gain fiber surface area. High-power ultrafast fiber lasers usually contain four modules, ultrafast fiber oscillators, optical parameters management, ultrafast fiber amplifiers, and nonlinear compression. Ultrafast fiber oscillators provide seed lasers to achieve high-power ultrafast fiber lasers. A qualified mode-locked fiber oscillator has long-term stability and a proportional repetition shared rate corresponding to the requirements of high-power fiber amplifications. Optical parameters management plays a key role in inhibiting uncompensated nonlinear effects and enabling high-energy pulse output with good pulse quality after optical pulse stretching, high power fiber amplification, and optical pulse compression. The ultrafast fiber amplifiers are key modules to scale up the average power of the stretched-signal pulses. Unfortunately, the uncompensated nonlinear phase introduced by the high-peak power of the signal pulse distorts the pulse profile during its propagation in the fiber system. Based on the well-managed optical parameters of fiber lasers, the well-known fiber amplification methods, such as chirped-pulse, divided-pulse, and pre-chirp managed amplifications are making a significant breakthrough in achieving high-power ultrafast fiber lasers. The pulse duration after high-power fiber amplification is hundreds of femtoseconds limited by the gain-narrowing effect. Therefore, a further cascaded nonlinear compression stage is needed for shortening the amplified pulses, which can realize single/few optical cycle pulse duration to fulfill the requirements of the state-of-the-art physical experiments. With their excellent optical characteristics, the fast-developing high-power fiber lasers can play an increasingly important role in multiple applications.

Progress Progress in developing ultrafast fiber oscillators, optical parameters management, ultrafast fiber amplifiers, and nonlinear compression are summarized in this paper, and latest published results are discussed by illustrating the advantages and disadvantages of different methods. The highest repetition rate of fiber oscillators reported using the method of nonlinear polarization rotation is 1 GHz provided to be useful in astronomical optical frequency comb, pulse stacking, and the cavity-enhanced high harmonic generation. The highest average output power and pulse energies are 1.98 W and 684 nJ, which are achieved with the nonlinear loop mirror mode-locking scheme, respectively. Applying a semiconductor saturable absorber mirror to the mode-locked fiber laser can generate an output mode-locked laser with the repetition rate range of 10 kHz–1 GHz and sub-μJ pulse energy. As a newly invented mode-locked method, Mamyshev mode-locked fiber laser has attracted attention for its broadband optical spectrum, high-pulse energy output, and high-peak power. As the seeder for a high-power ultrafast fiber laser system, further efforts need to be taken in developing a more stable fiber oscillator with better parameters.

Relying on optical parameter management, current ultrafast fiber amplifiers are realized with different amplification methods, such as chirped-pulse, divided-pulse, and pre-chirp managed amplifications. The highest average output power of 830 W at 1 μm was reported by applying the chirped-pulse amplification. Limited by the transverse mode instability and thermal damage threshold, there is one research direction for further improvement that can be realized by searching for new gain materials with better optical performances. Combining the chirped-pulse and multi-channel divided-pulse amplifications, the highest average output power of 10.4 kW was obtained in a 12-channel fiber laser amplifier. 36 fs mode-locked pulses with 100 W average power were achieved with the method of pre-chirp managed amplification, avoiding adding a cascaded nonlinear compression stage. Apart from the aforementioned amplification methods, coherent pulse stacking method is also an efficient way in realizing ultrafast fiber laser with high-pulse energy. Pulse energy of 10 mJ was achieved with the coherent pulse stacking based on the high-power ultrafast fiber laser source.

It is difficult to realize sub-100 fs or even shorter pulse durations in a high-power fiber chirped pulse amplification system due to the gain-narrowing effect. Therefore, a further nonlinear compression stage is necessary to satisfying the state-of-the-art applications, requiring short pulse duration. Multipass cells with quartz sheet/noble gas and noble-gas-filled hollow-core fibers are two common constructions in building the nonlinear compression stage, which are illustrated in the nonlinear compression section of this paper. The pulse duration can be compressed to 22 fs, and a pulse energy of 15.6 μJ was realized in the multipass cell construction. Using the noble-gas-filled hollow-core fibers, pulse duration was shortened to approximately 4.3 fs corresponding to a 1.6 optical cycle with a pulse energy of 1 mJ.

Conclusions and Prospect In this paper, the high-power ultrafast fiber laser systems are introduced. Research and development status of high-power ultrafast fiber lasers are illustrated along with introducing principles and internal relations of four fundamental modules of ultrafast fiber oscillators, optical parameters management, ultrafast fiber amplifiers, and nonlinear compression. Depending on the fast-developing requirements from multiple state-of-the-art applications, more efforts need to be taken. Further research directions in developing high-power ultrafast fiber lasers have prospected. One promising way is investigating new fiber materials with promising better optical parameters compared to fused silica. Further, making contributions in developing the aforementioned fiber amplification methods is also an efficient way in developing fiber lasers with above-average power, higher-pulse energy, and shorter pulse duration. Newly designed optical fiber amplification methods still need to be invented by carefully considering the optical characteristics of fiber gain material and theoretical nonlinear optical conditions. High-power ultrafast fiber lasers can play a key role in multiple state-of-the-art applications relying on the development of searching for more functional fiber gain materials, optimizing aforementioned amplification techniques, and inventing new methods in amplifying high-power ultrafast fiber lasers.

Key words laser optics; high-power laser; ultrafast laser; fiber laser; nonlinearity management; phase management

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