第 48 卷 第 4 期/2021 年 2 月/中国激光　　封底文章　特邀综述

中国激光

激光相干合成的研究进展:2011—2020

周朴*，粟荣涛，马阎星，马鹏飞，吴坚，李灿，姜曼

国防科技大学前沿交叉学科学院，湖南 长沙 410073

摘要　本文回顾了过去 10 年激光相干合成领域取得的重要进展，总结了可合成激光模块性能提升的标志性成果，梳理了相干合成使能技术取得的重要突破，展示了不同类型激光相干合成取得的成果及其多样化应用，并对激光相干合成领域的发展进行了展望。

关键词　激光器；相干合成；高能激光；光纤激光；固体激光；半导体激光

中图分类号　O436　　**文献标志码**　A　　**doi**：10.3788/CJL202148.0401003

1　引　　言

对多束激光进行相干合成是实现提升激光功率的同时保持光束质量的有效技术途径，它的发展基本和激光技术的发展同步，并已经应用在几乎各种类型的激光器中[1]。2009 年，美国 Northrop Grumman 公司以光纤激光作为种子源，利用主动相位控制实现了 7 路万瓦级板条放大器的相干合成，获得超过百千瓦级固体激光输出[2]，成为激光发展史上的重要里程碑事件。近 10 年来，随着可合成激光模块的性能不断提升和相干合成使能技术不断发展，各种类型的激光相干合成成果不断涌现[3-6]，并发展了大量基于相干合成的大型研究计划[7-11]。本文在文献[1]的基础上，梳理近 10 年（2011—2020）来激光相干合成领域的关键技术突破和代表性研究成果，总结激光相干合成技术已经实现的重要应用，呈现该领域的发展态势和全貌，展望激光相干合成技术的未来发展。

2　可合成激光模块的性能不断提升

尽管相干合成具有提升输出功率的同时提升光束质量的效果，但从以往的发展历程分析[1]，系统并非对参与合成的单束激光性能没有要求。为保证相干合成系统的输出性能，一般会对参与合成的单束激光提出模块化、紧凑化、高效率等需求。近年来，以光纤激光、固体激光、半导体激光为代表的各种类型的激光器性能均取得了显著提升，为相干合成系统的研制提供了高性能单元模块。

2.1　光纤激光

光纤激光是目前相干合成系统采用最多的激光器类型[4-5,12]。自从 1988 年发明双包层光纤以来，单束光纤激光的输出功率不断提升；与此同时，受限于非线性效应和模式不稳定效应等因素的影响，单束光纤激光的输出功率存在物理极限[13-17]，对多束激光进行相干合成是构建高功率光纤激光系统的重要技术途径[8,18]。相干合成对单元激光的结构和参数有较为严格的要求，并非所有类型的光纤激光都能用来相干合成。由于单元激光的性能、多束光纤激光控制能力等因素的限制，在 21 世纪前 10 年，基于光纤激光的相干合成系统性能并不十分突出，千瓦级相干合成系统直到 2010 年底才首次实现[19]，与当时基于固体激光的百千瓦级相干合成系统相比有着明显差距[2]。

近 10 年来，受益于先进制造（如飞秒激光加工）、大科学工程（如引力波探测）等应用领域的驱动和激光材料制备、非线性效应调控等技术的不断突破，单元光纤激光的性能得到了显著提升，并正在朝着三个“任意”：任意功率、任意波长和任意输出模式

收稿日期：2020-10-15；**修回日期**：2020-12-11；**录用日期**：2021-01-18

基金项目：国家自然科学基金（62035015）、湖南省自然科学基金创新研究群体项目（2019JJ10005）

* **E-mail**：zhoupu203@163.com

的方向发展[20]。比如单频光纤激光的输出功率由2008 年的 200 瓦级提升至 2020 年的 500 瓦级[21]，窄线宽光纤激光的输出功率由 2010 年的千瓦级提升至 2020 年的 4 千瓦级[22-23]，飞秒光纤激光的平均功率突破了千瓦级[24]；此外，超高电光转换效率(大于 50%)光纤激光[25]和紧凑型光纤激光[26]等高性能工业级激光的推出为构建模块化的激光阵列提供了技术基础。与此同时，相干合成技术也被应用于多种类型的光纤激光系统中，如纳秒激光/皮秒激光/飞秒激光、1.0 μm/1.5 μm/2.0 μm 等[27-32]，大大加速了光纤激光技术的发展。

2.2　固体激光

在 21 世纪初期，以 Nd∶YAG 板条激光为基本合成单元的固体激光相干合成是激光技术领域的研究热点[33-34]，美国诺格公司先后实现 2 路、4 路、7 路 Nd∶YAG 板条激光相干合成，并基于相干合成技术在国际上率先实现百千瓦级固体激光系统[35]。但由于当时单元激光电光效率提升、光束质量保持等存在较大技术挑战，板条固体激光相干合成的后续报道并不多见；文献[36]报道的万瓦级板条激光的光光转换效率约为 30%、光束质量约为 7 倍衍射极限，这与同期万瓦级光纤激光的指标相比有较大差别。近年来，研究人员通过腔外光束净化和引入 Yb∶YAG 介质等方式，显著提升了光束质量和光光效率。2018 年，中国科学院理化技术研究所和清华大学课题组合作实现了万瓦级(10.8 kW) Nd∶YAG 板条激光 2.6 倍衍射极限输出[37]；中国科学院理化技术研究所和中国科学院光电技术研究所课题组合作实现了 2 万瓦级(24.6 kW) Nd∶YAG 板条激光 1.5 倍衍射极限输出[38]。由于具有更小的量子亏损和更低的产热[39-43]，采用 Yb∶YAG 介质有望比 Nd∶YAG 介质实现更好的光束质量和光光效率。2016 年，中国工程物理研究院实现了 3 千瓦级(3.54 kW) Yb∶YAG 激光，光光转换效率 41%[39]；2018 年，中国工程物理研究院等单位实现了 2 万瓦级(22.3 kW) Yb∶YAG 板条激光高功率输出，光束质量为 3.3 倍衍射极限，提取效率为 36%并有望提升到 46%[40]；2020 年，中国科学院理化技术研究所和清华大学课题组合作实现了 2 万瓦级(21.2 kW) Yb∶YAG 板条激光 1.94 倍衍射极限输出、光光转换效率为 30%[43]。综上，通过采用光束净化、Yb∶YAG 介质和温度管理[44]等方式，高功率固体激光的光束质量和效率等参数取得了明显进展，若再次与相干合成技术结合，有望获得新的突破。

2.3　半导体激光

半导体激光具有效率高、体积紧凑、寿命长、可靠性好等优点，在通信、制造、医疗、科研等多个领域得到了广泛应用[45-47]。与光纤激光、固体激光相比，高功率半导体激光的光束质量相对较差，因此常被用作光纤激光和固体激光的泵浦源。提升输出功率的同时保证光束质量成为高功率半导体激光技术领域的研究热点，半导体激光相干合成就是其中的一种重要技术途径[48]。尽管半导体激光的合成路数很早就取得了巨大突破[49]，但由于合成单元的性能(效率、功率、光束质量等)限制，基于相干合成的半导体激光系统并没有实质性进展。近年来，随着芯片设计、材料生产和器件制备等技术的不断发展，半导体激光的性能不断提升，为半导体激光的相干合成提供了新的机遇。基于内腔光反馈技术和外腔光反馈技术的半导体激光已经分别实现了低于 10 kHz 和低于 100 Hz 的窄线宽输出[45]，德国 FBH 研究所、美国 nLight 公司等单位通过半导体光放大器实现了高功率输出的同时保持较好光束质量[50-51]。此外，半导体激光的亮度和效率等方面也取得了显著进步[46]：JDSU 公司于 2015 年报道了输出功率高达 29.5 W 的 950 nm 单管[52]，Fujikura 公司 2017 年报道了输出功率为 27 W、电光效率大于 60%的 915 nm 单管[53]，IPG 公司 2017 年报道了室温连续条件下转换效率高达 73%的 976 nm 单管[54]，Fujikura 公司 2019 年报道了室温连续条件下转换效率 72.5%的 975 nm 单管(20 W 输出功率时转换效率仍高达 66.7%)[55]。类比 2.1 小节总结的光纤激光单元性能提升的代表性成果，可以对类似光纤激光经典结构[54]的半导体激光相干合成系统的构建提供重要启发。值得注意的是，基于光谱合成的高功率半导体激光系统的亮度已经接近或者达到相同功率量级的固体激光系统[56-57]。

3　相干合成使能技术不断发展

相干合成通过各路激光的参量控制和激光阵列的孔径填充，实现激光阵列的同相位、高占空比输出，达到激光阵列亮度提升的目的。典型的相干合成系统结构如图 1 所示，种子激光由分束器分为多路，每一路激光经过相位调制器(PM)、延迟线(DL)、放大器(AMP)和激光准直器(CO)等器件后，再利用合束装置实现各路激光的高占空比合成。为了对合成效果进行评价，同时为参量控制提供反

馈信号，通常利用光束分光镜（BS）提取小部分激光进行误差探测，同时提取小部分光经过透镜形成远场光斑。由图 1 可以看出，对各路激光的相位、倾斜、偏振、光程和高阶像差进行控制以及对阵列激光进行孔径填充获得高占空比是获得良好的合成效果的关键技术。近年来，上述使能技术均取得了重要进展，为获得高性能相干合成激光系统奠定了技术基础。

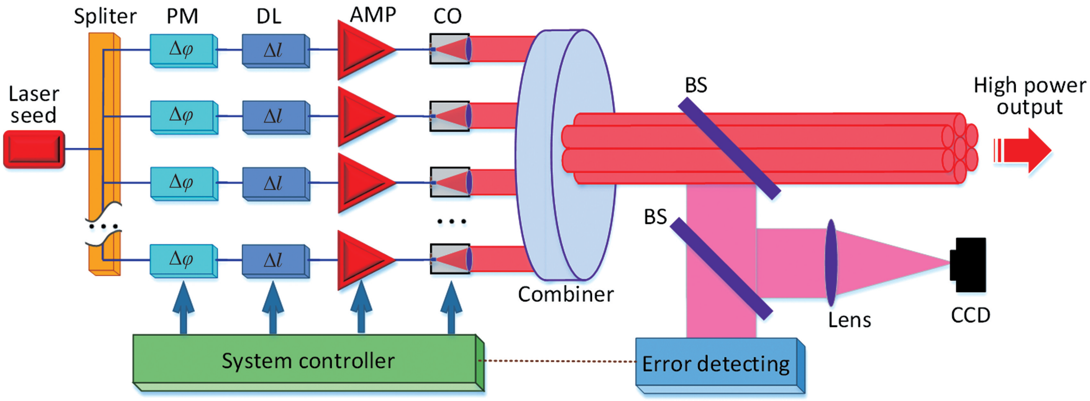

图 1 主动相位控制相干合成系统的结构示意图

Fig. 1 Schematic setup of active phase control coherent beam combining system

3.1 相位控制技术

根据相位控制的物理机理，可以将其分为被动相位控制和主动相位控制两类。被动相位控制是通过一定的能量耦合机制或者非线性相互作用实现各路激光相位起伏的自动补偿。与主动相位控制相比，无需复杂的相位控制系统，结构相对简单。被动锁相方法主要有外腔法[58-62]、倏逝波耦合法[63-64]、全光纤自组织法[65-67]和相位共轭法[68-69]等。2011 年，中国科学院上海光学精密机械研究所采用单模光纤滤波环形腔实现了 8 路光纤放大器的相干输出，总功率达到 1.09 kW[70]。

主动相位控制利用相位检测和控制系统对各路激光的相位起伏进行补偿。根据相位误差的探测方式，可以将其分为直接探测和间接探测两类。直接探测采用外差法[34,71]、Hänsch-Couillaud（H-C）偏振探测[72-73]、剪切干涉[74]、参考光干涉[75]和干涉图像[76]等方法获取各路激光之间的活塞相位误差，具有算法迭代步数较小、控制带宽较高等优点，但是误差探测系统较为复杂。间接探测利用光电探测器提取合成光束的远场中央主斑能量，利用随机并行梯度下降（SPGD）算法[77-78]、多抖动算法[79-80]和单抖动算法[81]等进行优化迭代，使其达到最大值。间接探测具有结构简单的优点，但是对算法的收敛速度提出了较高要求。近十年来，主动相位控制的激光路数和总功率得到了有效提升，已经实现了最高百路级路数和万瓦级功率的激光阵列相位锁定，代表性研究结果如表 1 所示。

表 1 相干合成主动相位控制代表性研究成果

Table 1 Representative research results of active phase control coherent beam combining

Method	Year	Institution	Result	Reference
SPGD	2011	Massachusetts Institute of Technology	8 fiber lasers with 4 kW overall power	[78]
	2014	National University of Defense Technology	32 low power fiber lasers	[82]
	2016	University of Dayton	21 fiber lasers with 0.5 kW overall power, target-in-the-loop over 7 km	[83-84]
	2019	National University of Defense Technology	60 low power fiber lasers	[85]
	2020	National University of Defense Technology	7 fiber lasers with 8 kW overall power	[86]
	2020	National University of Defense Technology	107 low power fiber lasers	[87]

续表

Method	Year	Institution	Result	Reference
Multi-frequency dithering	2011	Air Force Research Laboratory	16 fiber lasers with kW level overall power	[88]
	2014	Northrop Grumman	3 fiber lasers with 2.4 kW overall power	[80]
	2016	Air Force Research Laboratory	5 fiber lasers with 4.9 kW overall power	[89]
	2018	Friedrich Schiller University Jena	4 pulsed fiber lasers with 3.5 kW overall power	[90]
	2020	Friedrich Schiller University Jena	12 pulsed fiber lasers with 10.4 kW overall power	[91]
Single frequency dithering	2010	National University of Defense Technology	9 fiber lasers with 1.08 kW overall power	[92]
	2016	National University of Defense Technology	4 fiber lasers with 5.02 kW overall power	[93]
	2017	China Academy of Engineering Physics	30 low power fiber lasers	[94]
Quadriwave lateral shearing interferometry	2011	Thales Research & Technology	64 low power fiber lasers	[74]
Reference beam interference	2014	Thales Research & Technology	16 low power fiber lasers	[75]
	2020	Thales Research & Technology	61 low power pulsed fiber lasers	[95]
Phase-intensity mapping	2017	Université de Limoges	37 fiber lasers with 30 W overall power	[96]

为了进一步提高相位控制带宽，研究人员从多个层面上进行了研究：1）对现有算法进行改进，提出了自适应 SPGD 算法、正交编码抖动算法等算法[97-100]；2）探索新的相位探测与控制方法，提出了基于倾斜调干涉和人工智能算法等的相位误差解算方法[101-105]；3）从体系上进行改进，利用分组控制、级联控制等方法提升控制带宽[106-108]。

3.2　倾斜控制技术

为了使各路激光在目标处进行有效重叠，需要控制各路激光的倾斜像差。静态倾斜像差控制可以利用高精度的光学调节架实现。由于热效应的影响，高功率激光的输出光斑通常存在动态抖动；在需要对激光进行远距离传输的应用中，大气湍流也会产生随机的倾斜误差。因此，为了在上述场景中获得较好的相干合成效果，必须进行动态的倾斜控制。最常见的倾斜控制方法就是使用快速倾斜镜，倾斜镜通过外加压电控制信号，改变反射镜面的整体倾斜量。2012 年，国防科技大学采用快速倾斜镜对 2 路百瓦级光纤激光进行倾斜控制，实现了 350 W 光纤激光有效相干合成[109]。倾斜镜具有精度高、响应快、技术成熟等优点，但是当阵列数目较多时，系统光路将过于复杂。

为了实现光纤激光阵列倾斜控制的紧凑化，研究人员提出了自适应光纤准直器（AFOC）的技术方案。AFOC 通过压电陶瓷驱动输出光纤，改变其在准直透镜焦平面处的位置，实现准直光束的倾斜控制和激光准直的一体化设计，具有惯性小、谐振频率高、结构紧凑等优势，适合应用于阵列光纤激光系统。2011 年、2016 年，美国 Dayton 大学的 Vorontsov 课题组在此前研制的 AFOC[110] 的基础上，构建基于 AFOC 的相干阵列系统，在 7 km 传输距离上先后开展了 7 路[111] 和 21 路[83] 目标在回路实验。2011 年，中国科学院光电技术研究所成功研制了 AFOC，并实现了 3 路光纤激光的相干合成[112]；随后，基于自研的 AFOC 搭建光纤激光阵列，开展了目标在回路实验研究[113]。千瓦级的光纤激光一般采用光纤端帽输出，这就需要 AFOC 的能动器件具有更大的推力，2014 年，国防科技大学研制了基于柔性铰链和光纤端帽的 AFOC[114]，并开展了实验研究[115-116]。基于 AFOC 的相干合成倾斜控制代表性成果如表 2 所示。

表 2　基于 AFOC 的相干合成倾斜控制代表性成果

Table 2　Representative research results of AFOC-based tilt control in coherent beam combining

Year	Institution	Result	Reference
2011	University of Dayton	7 low power fiber lasers, target-in-the-loop over 7 km	[111]
2011	Institute of Optics and Electronics	3 low power fiber lasers	[112]
2012	Northrop Grumman	5 low power fiber lasers	[117]
2013	Institute of Optics and Electronics	7 fiber lasers with 10 W level overall power	[118]
2014	National University of Defense Technology	2 fiber lasers with 10 W level overall power	[115]
2016	University of Dayton	21 fiber lasers with 0.5 kW overall power, target-in-the-loop over 7 km	[83-84]
2017	National University of Defense Technology	7 fiber lasers with 10 W level overall power	[116]
2018	Institute of Optics and Electronics	7 fiber lasers with 10 W level overall power, target-in-the-loop over 200 m	[113]
2018	National University of Defense Technology	6 fiber lasers with 10 W level overall power, target-in-the-loop over 800 m	[119]

3.3　偏振控制技术

为提升合成效率，一般要求各路激光的偏振方向相同。根据偏振控制施加的位置，可以将其分为末端偏振控制和前端偏振预补偿两大类[120-121]。末端偏振控制就是在激光输出端利用半波片[29,122]、偏振合束器[123-124]、马赫-曾德尔(M-Z)干涉仪[125]等方式对激光的偏振方向进行控制；由于直接对输出的激光进行操作，控制直接有效，灵活度较高，但是输出功率和控制带宽均受限于偏振控制器件。在光纤激光相干合成系统中，通常采用保偏光纤放大器进行功率放大，使激光保持较好的偏振特性，再在输出端利用半波片进行静态的偏振调节，从而达到良好的相干合成效果。但是，保偏器件价格昂贵，保偏光纤中模式不稳定性等效应更强，功率提升更加困难。一条有效的途径就是搭建非保偏放大器，在放大器的前端利用偏振控制器进行偏振预补偿，从而实现高功率的线偏振激光输出[126]。采用该方法，美国 Northrop Grumman 公司、国防科技大学、中国工程物理研究院等单位实现了千瓦级窄线宽线偏振激光输出[127-129]，并在相干合成系统中验证了该技术的可行性[130-131]。图 2 所示为国防科技大学课题组的千瓦级高功率光纤放大器偏振控制系统结构。系统由窄线宽激光器种子和三级光纤放大器组成，通过白噪声源对单频光纤激光器进行相位调制产生窄线宽激光种子，主放大器最大功率为 1.43 kW(受到泵浦功率限制)。利用基于 SPGD 算法的偏振控制技术对种子激光的注入偏振态进行控制，在最大输出功率下激光束的偏振消光比大于 11 dB，线性偏振激光约为总功率 93%。美国 Northrop Grumman 公司在2012年验证5路光纤激光相干合成系统中

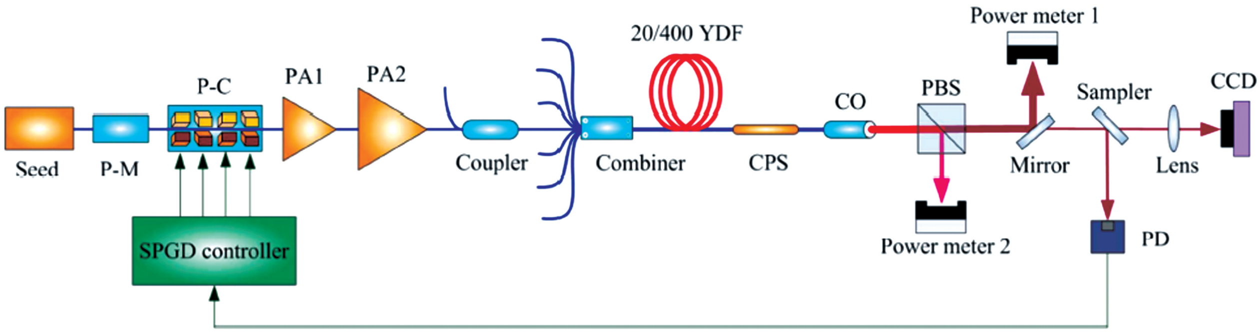

图 2　kW 级窄线宽光纤放大器中的偏振控制系统结构[129]

Fig. 2　Schematic diagram of polarization control system for narrow linewidth fiber amplifier[129]

的预补偿偏振控制技术的基础上[130]，与美国空军实验室开展合作，利用该技术在 2014 年和 2016 年先后实现了 3 路 2.4 kW 和 5 路 4.9 kW 的非保偏光纤放大器高效相干合成[80,89]。

3.4　光程控制技术

各路激光之间光程差会引起群延时效应，降低相干合成效率。为了使合成效率达到 99%，各路激光的光程差均方根值应小于 0.1L_{coh}，L_{coh} 表示相干长度[132-133]。对于脉冲激光相干合成系统，除了群延时外，光程差还会引起时域误差和非线性相移误差[134-136]。当激光线宽较窄、脉宽较宽时，对光程差的要求并不高。如线宽在 GHz 量级、脉宽在 ns 量级时，只需将各路激光的光程差控制到厘米量级就能获得良好的相干合成效果[135]。此时，采用空间光路调节[27]和被动光纤匹配熔接[28]等方法就能达到光程控制要求。随着线宽的增加，系统对光程控制的精度要求也随之提高，通常采用动态光纤延迟线[29,75,78,89]、压电陶瓷高精度空间位移器[91,137]、光纤拉伸器[133,138]等高精度光程控制器件。当线宽增加到 10 nm 量级时，需要将光程精度控制到 10 μm 量级[136]。此时，需要对各路激光直接的光程差进行实时控制，以获得理想的合成效果[91,133,137-139]。

图 3 为国防科技大学课题组设计的适用于高精度实时控制光程差的实验系统[137]。首先，调节空间光路，即准直器到偏振合束器的距离，使自由空间传输部分光程基本一致；其次，熔接被动光纤，使光纤传输部分的光程基本一致，同时起到色散补偿的作用，上述两项操作的精度大约可以控制在厘米量级；第三，调节光学延迟线（ODL）以消除固定光程差：ODL 调节精度高（约为 0.3 μm）、范围广（0～180 mm），但响应速度慢（3 μm/s），适用于补偿固定光程差，但不足以达到光程慢漂移自适应补偿的应用要求。最后，通过压电陶瓷相位调制器（FS）实现光程差漂移的自适应补偿：FS 控制精度高（0.035 μm/V）、响应速度快（1 阶谐振频率约为 50 kHz），可以满足光程差慢漂移自适应控制的要求。

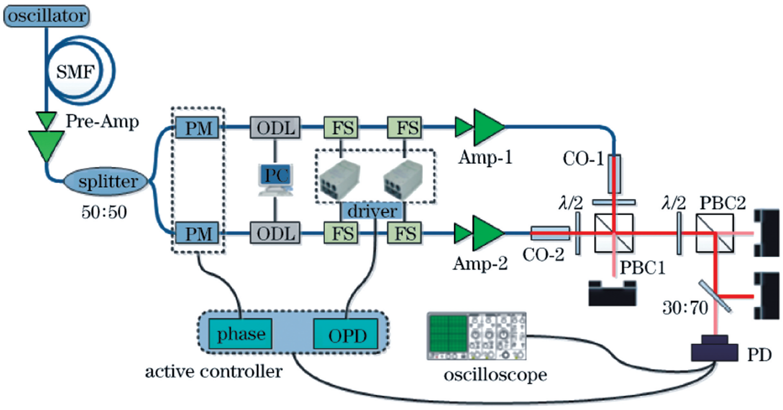

图 3　高精度光程差实时控制系统[139]

Fig. 3　High precision optical path difference real-time control system[139]

3.5　高阶像差控制技术

从像差的角度而言，3.1 节、3.2 节介绍的相位控制和倾斜控制指的是单元激光的低阶像差。为了获得理想的相干合成效果，通常要求各路激光具有良好的光束质量且光斑形态保持一致；为此一般追求单元激光输出光束为基模。由于热效应等因素的影响，高功率单元光束（包括半导体激光、固体激光、光纤激光等）往往含有高阶模成分[47,140-141]；对于光纤激光而言，还存在从波导到自由空间的元件引入的像差因素[142-143]。一般需要引入模式控制技术或者自适应光学方法进行控制或校正[144-147]。图 4(a) 为国防科技大学课题组设计的大功率离焦补偿型准直系统的原理图[142]，其中 Endcap 为光纤端帽，F1 和 F2 为两个组合式透镜，用来实现光束的扩束、准直。为了实现离焦补偿功能，在准直器机械装配时设计透镜 F1 和 F2 之间距离可调；F1 和 F2 组合式透镜的等效焦距将具备可调节的功能。通过改变组合式透镜的等效焦距，便可以实现离焦像差的补偿。图 4(b) 为该大功率离焦补偿型准直系统的激光输出测试结果，可以看出，随着输出功率的增加，透镜窗口组建的准直系统基本不会引起光束质量的退化，可以用于大功率相干合成系统中[143]。

此外，由于模体积引入的功率提升潜力，近年来也有不少产生纯净高阶模式激光的报道。以光纤激光为例，通过光栅选模等方式，研究人员已经实现了百瓦级高阶模式激光输出[148-151]。

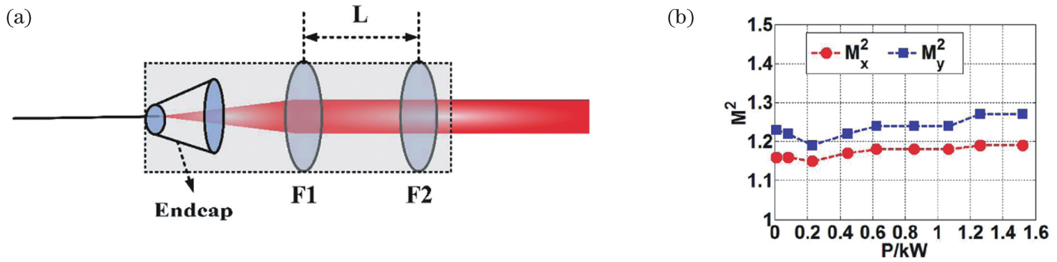

图 4　大功率离焦补偿型准直系统。(a) 工作原理[142]；(b) 实验结果[143]

Fig. 4　High power defocus compensation collimation system. (a) Principle schematic[142]; (b) experimental results[143]

3.6　孔径填充技术

为了提高阵列光束远场光斑的能量集中度，通常还需要利用合束器提升阵列光束的占空比。其技术方案可以分为分孔径合成和共孔径合成两类。分孔径合成通过压缩阵列光束的占空比，来减少阵列光束远场光斑中旁瓣的能量占比，主要方法有准直器直接拼接、功率合束器、空间光路拼接和微透镜阵列等。共孔径合成通过使各路激光在空间上完全重合，从而形成一束激光输出，主要方法有M-Z 干涉仪、自成像光波导[152]、相干偏振合成和衍射光学元件(DOE)等。分孔径合成是对各路激光的紧密拼接，合成过程中不存在能量损失，但是远场光斑的能量会向旁瓣分散，导致中央主斑的能量损失。分孔径合成的关键就是要保持各路激光在远场的重合度，尽可能压缩占空比，提升远场光斑中央主斑的能量占比，通常用桶中功率(PIB)作为评价指标。共孔径合成是将各路激光在近场就合为一束，因此在远场不存在旁瓣，但是在合束过程中存在能量损失。共孔径合成的关键就是保持各路激光在近场和远场的重合度，减少合成过程中的能量损失，提升合成效率。近年来，在路数和功率提升等方面具有较大提升的方法有：准直器直接拼接、微透镜阵列、衍射光学元件和相干偏振合成等，代表性结果如表 3 所示。

表 3　孔径填充的代表性研究成果

Table 3　Representative research results of aperture-filling

Method	Year	Institution	Result	Reference
Collimators array	2017	Université de Limoges	37 fiber lasers with 30 W overall power, PIB was 36%	[96]
	2017	China Academy of Engineering Physics	30 low power fiber lasers, PIB was 41.65%	[94]
	2019	National University of Defense Technology	60 low power fiber lasers, PIB was 34.7%	[85]
	2020	National University of Defense Technology	7 fiber lasers with 8 kW overall power, PIB was 18.76%	[86]
	2020	National University of Defense Technology	107 low power fiber lasers, PIB was 22.47%	[87]
Microlens array	2011	Massachusetts Institute of Technology	8 fiber lasers with 4 kW overall power, PIB was 58%	[78]
	2011	Thales Research & Technology	64 low power fiber lasers, PIB was 34%	[74]
	2020	Thales Research & Technology	61 low power pulsed fiber lasers, PIB was 48%	[95]
Fiber bundle	2020	Civan Advanced Technologies	32 fiber lasers with 16 kW overall power	[153]
DOE	2012	Massachusetts Institute of Technology	5 fiber lasers with 1.93 kW overall power, M^2 was 1.1, combination efficiency was 79%	[154]
	2014	Northrop Grumman	3 fiber lasers with 2.4 kW overall power, M^2 was 1.2, combination efficiency was 80%	[80]
	2016	Air Force Research Laboratory	5 fiber lasers with 4.9 kW overall power, M^2 was 1.1, combination efficiency was 82%	[89]

续表

Method	Year	Institution	Result	Reference
CPBC	2012	National University of Defense Technology	8 low power fiber lasers, combination efficiency was 92%	[155]
	2013	Friedrich Schiller University Jena	4 pulsed fiber lasers with 530 W overall power, combination efficiency was 93%, M^2 was 1.2	[156]
	2014	National University of Defense Technology	4 fiber lasers with 680 W overall power, combination efficiency was 75.2%	[157]
	2016	Friedrich Schiller University Jena	8 pulsed fiber lasers with 1 kW overall power, combination efficiency was 91%	[158]
	2017	Friedrich Schiller University Jena	16 pulsed fiber lasers with 1.83 kW overall power, combination efficiency was 82%	[72]
	2017	National University of Defense Technology	4 fiber lasers with 5.02 kW overall power, combination efficiency was 93.8%	[93]
M-Z interferometer	2016	Laboratoire ARTEMIS	2 fiber lasers with 80 W overall power, combination efficiency was 96%	[159]
	2018	Friedrich Schiller University Jena	4 pulsed fiber lasers with 3.5 kW overall power, combination efficiency was 88.2%	[90]
	2020	Friedrich Schiller University Jena	12 pulsed fiber lasers with 10.4 kW overall power, combination efficiency was 96%	[91]

3.7　小　　结

上述使能技术并不是相互独立的，在实际相干合成系统中往往是相互耦合或者同步实现的。文献[116]报道的 AFOC 设计就同时具备倾斜控制和孔径填充功能，基于该 AFOC 阵列实现了接近 50%的主瓣能量占比。文献[160]提出了一种基于四象限探测器的同时实现倾斜和相位控制的方法，光束指向控制精度达到 0.19 μrad、相位锁定残差为 0.7°，合成总体效率达到 99%。此外，由于光程与相位的关系，如能实现对光程的高速高精度控制，则有望一并实现相位的实时控制。

4　相干合成研究成果不断涌现

4.1　半导体激光相干合成

2011 年以来，美国麻省理工学院、Oak Ridge 国家实验室、Clemson 大学、Corcoran 公司，新加坡南洋理工大学，法国 Paris-Saclay 大学、Thales 研究所，德国 FBH 研究所，中国科学院长春光学精密机械与物理研究所等单位[161-174]均开展了半导体激光相干合成研究。其中比较有代表性的结果有：2011 年美国麻省理工学院报道通过主动相位控制的方法实现 218 单元激光相干合成，总输出功率 38.5 W[163]；2019 年法国 Paris-Saclay 大学报道通过主动相位控制的方法实现 4 单元激光相干合成，总输出功率 22.7 W 时保持接近衍射极限的光束质量[173]。

虽然目前半导体相干合成的输出功率并没有呈现出明显的优势，但在中红外半导体激光输出功率提升等特殊领域方面表现出了巨大潜力[161-162]。2011 年，法国 Thales 研究所实现了 5 束 4.65 μm 中红外激光半导体激光被动相位控制相干合成，实验原理如图 5 所示[162]。合成后的激光输出功率为 550 mW，光束质量为 $M_x^2<1.6$、$M_y^2<1.2$（与合成单元的光束质量接近），合成效率为 66%。

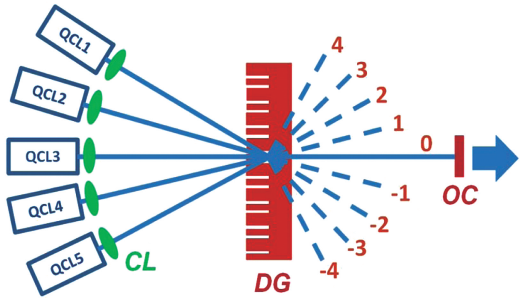

图 5　5 束半导体激光相干合成结构示意图[162]

Fig. 5　Schematic setup of coherent beam combining of five diode lasers [162]

4.2　固体激光相干合成

如 2.2 节所述，21 世纪前 10 年固体激光相干合成领域取得了巨大成就，实现了首个百千瓦级固体激光系统。近 10 年来，并没有进一步提升平均功率的结果报道，研究人员将重点转至相位控制方法、脉冲激光相干合成等领域[175-181]。相位控制方法方

面，中国工程物理研究院[175]和韩国科学技术研究院[177]的研究人员通过方波信号抖动主动相位控制和基于受激布里渊散射被动相位控制的方法，实现了 2 路板条固体激光和 4 路高重复频率固体激光相干合成。2018 年，中国科学院半导体研究所的科研人员基于级联 Michelson 复合腔的方法实现 3 束 Nd：YAG 激光相干合成，合成前单束激光的功率约为 65 W、光束质量因子 M^2 约为 5.5，合成后的激光输出功率为 124.4 W、光束质量因子约为 1.36[181]。脉冲激光相干合成方面，2013 年，原武汉军械士官学校的研究人员运用角锥作为合成元件，实现了 6 束脉冲固体激光相干合成，总输出能量为 15.3 J、输出激光重复频率为 10 Hz、合成效率达 95.6%，实验系统如图 6 所示[176]。2014 年，德国耶拿大学的研究人员实现两路 Yb：YAG 单晶棒状固体激光放大器相干合成，合成后的光束能量为 3 mJ、峰值功率为 3.7 GW、脉宽为 695 fs，合成效率达 94%[178]。2019 年，中国科学院上海光学精密机械研究所的科研人员首次实现了两路钛宝石啁啾脉冲激光相干合成，合成激光的重复频率为 1 Hz，合成效率达 90%[179]。固体激光是超强激光的重要实现方式，对于高重复频率高平均功率超强激光和低重复频率超高峰值功率超强激光系统而言，相干合成都是重要发展方向[182]。

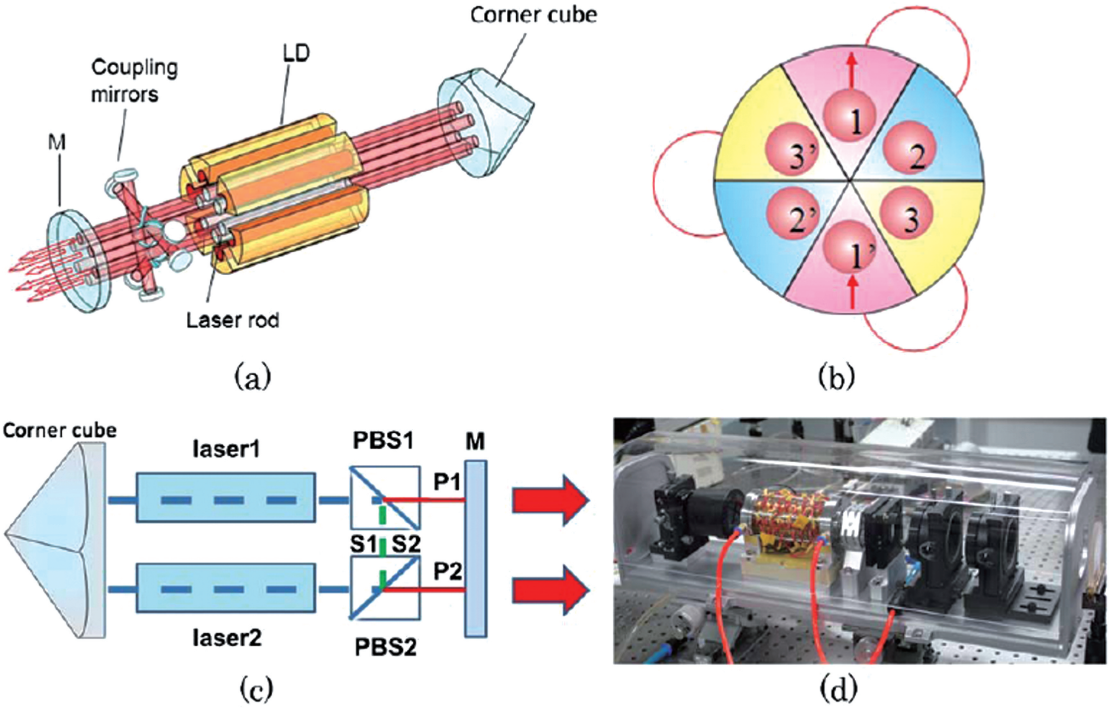

图 6　6 路固体激光相干合成系统[176]

Fig. 6　Schematic setup of coherent beam combining of 6 solid state lasers[176]

4.3　光纤激光相干合成

近年来，向大阵元数目扩展是光纤激光相干合成的重要发展方向之一。法国 Thales 研究所、美国 Dayton 大学、国防科技大学、中国工程物理研究院等单位都实现了数十路光纤激光的相干合成。2011 年法国 Thales 研究所利用剪切干涉技术实现了 64 路光纤激光的相干合成[74]。2014 年，国防科技大学利用并行梯度下降（SPGD）算法实现了 32 路光纤激光的相位锁定[82]。2016 年，美国 Dayton 大学实现了 21 路光纤激光的目标在回路相干合成（图 7）[83]；中国工程物理研究院利用方波扰动算法实现了 30 路光纤激光的相干合成[94]。2019 年，国防科技大学利用 SPGD 算法实现了 60 路光纤激光的相干合成[85]。2020 年，法国 Thales 研究所基于参考光干涉技术实现了 61 路飞秒光纤激光的相干合成[183]。国防科技大学实现了 107 路光纤激光相干合成，为目前公开报道的光纤激光相干合成最高路数[184]。

高功率系统论证是相干合成光源走向实用的关键。2011 年，国防科技大学基于单抖动算法实现了 9 路 1.08 kW 光纤激光相干合成，首次突破了千瓦输出功率[92]；同年，中国科学院上海光学精密机械研究所采用单模光纤滤波环形腔实现了 8 路 1.09 kW 总功率光纤激光相干合成[70]；美国空军实验室利用多抖动算法实现了16路输出功率为

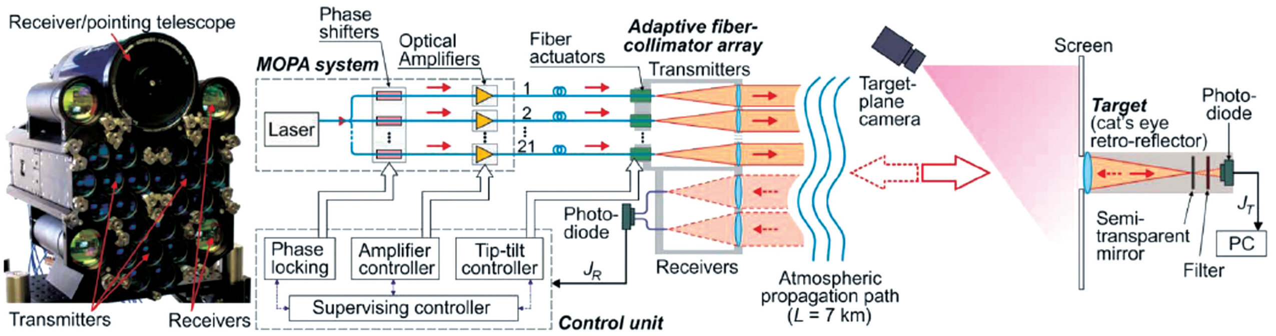

图 7　21 路光纤激光的目标在回路相干合成实验结构[83]

Fig. 7　Schematic setup of target-in-the-loop coherent beam combining of 21 fiber lasers[83]

1.4 kW 的相干合成；美国林肯实验室基于 SPGD 算法实现了 8 路光纤放大器相干合成，总输出功率为 4 kW[78]。2014 年，美国 Northrop Grumman 公司基于 DOE 实现了 3 路 2.4 kW 总功率的共孔径相干合成，合成效率 80%[80]。2016 年，美国空军实验室基于 DOE 实现了 5 路千瓦级光纤放大器的相干合成，总输出功率 4.9 kW，合成效率 82%[89]。2017 年，国防科技大学实现了 4 路 5.02 kW 总功率的相干偏振合成，合成效率 93.8%[93]。2019 年，国防科技大学实现了 7 路光纤激光的相干合成，总输出功率为 8 kW 量级[86]，系统在开环和闭环时的远场光斑如图 8 所示。2020 年，以色列 Civan 公司实现了 37 路输出功率为 16 kW 的光纤激光相干合成，为光纤激光相干合成公开报道的最高功率[153]。

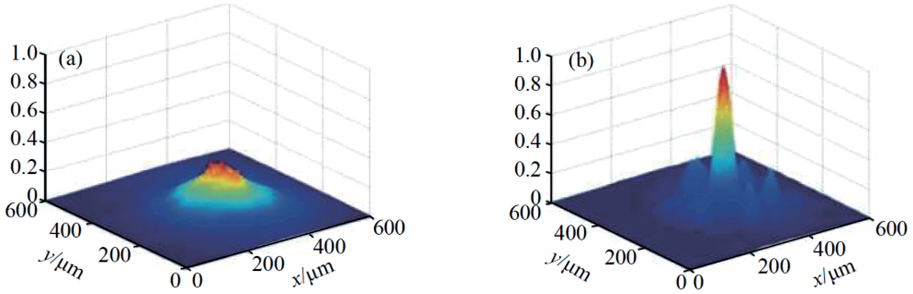

图 8　8 kW 级高占空比相干合成系统的远场光斑曝光图样[86]。(a)开环；(b)闭环

Fig. 8　Far-field spot exposure patterns of coherent beam combining system with 8 kW level high duty cycle[86]. (a) Open loop; (b) closed loop

除了以上两类代表性成果之外，相干合成技术还被大量应用于 2 μm 波段光纤激光的相干合成中[185-189]。2013 年，捷克科学院等单位的科研人员采用被动相位控制的方法实现了 2 路激光相干合成、总输出功率为 20 W[186]。2014 年，国防科技大学课题组采用主动相位控制方法实现 2 路单频光纤放大器相干合成，总输出功率突破百瓦级[187]。2015 年，德国耶拿大学等单位科研人员实现了 2 路超短脉冲掺铥光纤放大器相干合成，合成光束的峰值功率达 25 MW、脉宽为 830 fs，合成效率大于 90%[188]。2018 年，澳大利亚国防科技研究组等单位的科研人员采用主动相位控制的方法实现了 4 路掺钬光纤放大器激光相干合成[189]。近年来，2 μm 波段光纤激光取得了显著进展，全光纤结构单频掺铥激光输出功率突破了 300 W[190]、掺钬光纤激光输出功率突破了 407 W[191]；若与相干合成技术结合，有望实现更高性能的 2 μm 光纤激光系统。

4.4　超快激光相干合成

随着先进制造等领域对高功率超快激光需求的不断提升，超快激光相干合成已成为近十年来的研究热点之一，德、法、美、中等国的研究人员开展了深入研究，其中德国耶拿大学的研究最具有代表性。该单位研究人员于 2011 年实现了 2 路飞秒脉冲相干合成，平均功率为 30 W、脉冲能量为 3 mJ、峰值功率为 5.4 GW、合成效率为 89%[73]；2013 年实现了 4 路飞秒脉冲相干合成，平均功率为 530 W、脉冲能量为 1.3 mJ、峰值功率为 1.8 GW、合成效率为 93%[156]；2014 年实现了 4 路平均功率为 230 W、脉冲能量为 5.7 mJ、峰值功率为 22 GW、合成效率为 88%的相干合成[192]；

2016 年将合成路数扩展到 8 路，在重复频率为 996 kHz 的条件下，平均功率达到 1 kW[158]；2017 年将合成路数进一步扩展到 16 路，实现了平均功率为 1.83 kW、脉冲能量为 2.3 mJ、合成效率为 82%的相干合成[72]。2018 年，他们采用分光镜作为合束器件，实现了 4 路、平均功率为 3.5 kW 的飞秒脉冲相干合成[90]；2020 年，他们将路数扩展到 12 路，实现了平均功率为 10.4 kW 的飞秒脉冲相干合成（图 9）[91]，这在飞秒激光领域是一件具有里程碑意义的重要事件。

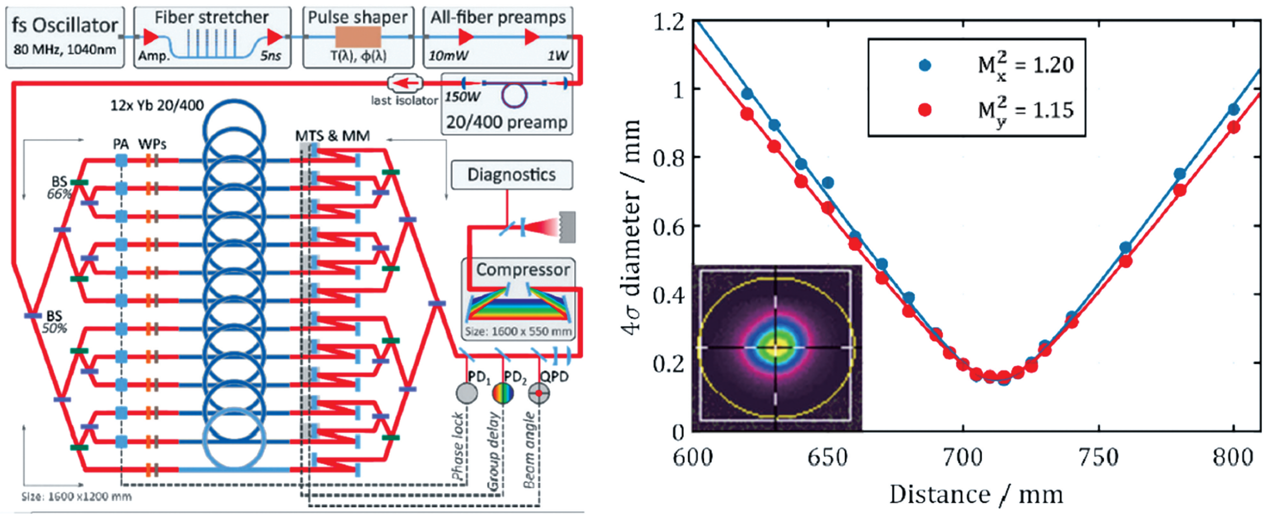

图 9　10.4 kW 平均功率飞秒脉冲光纤激光相干合成实验结构和结果[91]

Fig. 9　Experimental setup and results for coherent beam combining of femtosecond pulsed fiber lasers with 10.4 kW average power[91]

法国 Thales 研究所近年来也持续开展了飞秒脉冲相干合成研究，他们采用参考干涉法相位控制、微透镜阵列光束合成的技术方案，2017 年实现了 19 路飞秒脉冲相干合成的实验验证[117]；2018 年实现了 7 路飞秒脉冲相干合成，平均功率为 71 W、脉冲宽度为 216 fs[193]；2020 年，实现了 61 路飞秒脉冲相干合成的实验验证[95]，实验结构如图 10 所示。此外，法国南巴黎大学[194]、美国密歇根大学[195]、俄罗斯科学院[196-197]等单位也开展了相关研究，合成路数一般为 2～4 路。

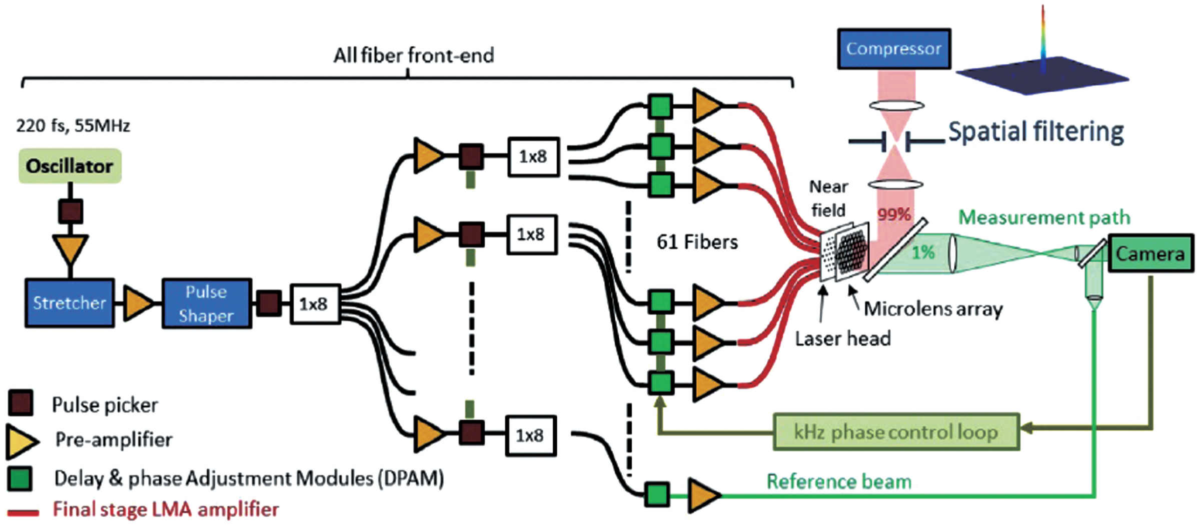

图 10　61 路飞秒脉冲光纤激光相干合成实验结构[95]

Fig. 10　Schematic setup of coherent beam combining of 61 femtosecond pulsed fiber lasers[95]

国内开展飞秒脉冲相干合成的单位主要有国防科技大学、上海理工大学、中国科学院上海光学精密机械研究所、天津大学和中国工程物理研究院等单位。2016 年，国防科技大学实现了 2 路飞秒脉冲光纤激光的相干偏振合成，平均功率为 313 W[198]；上海理工大学实现了 2 路、30.4 W 平均功率的飞秒

脉冲相干偏振合成[199]；中国工程物理研究院实现了 2 路飞秒固体激光的相干合成[200]；2017 年，中国科学院上海光学精密机械研究所实现了 2 路 100 Hz 重复频率的飞秒固体激光的相干合成[201]。

随着相干合成使能技术的进步，飞秒脉冲光纤激光相干合成已经从传统的空域合成向相干时域合成和相干光谱合成发展[3,202]。相干时域合成是对高重复频率的脉冲序列进行功率放大后，再通过时序合成，降低激光的重复频率，提升输出激光的峰值功率。相干光谱合成是为了克服单路光纤激光的增益带宽限制以及脉冲放大过程中的增益窄化效应，通过对不同频谱的激光进行相干合成，实现宽光谱、窄脉宽的激光输出。

相干时域合成主要有脉冲分割放大（DPA）和环形腔脉冲堆叠两种技术途径。德国耶拿大学[203]、法国南巴黎大学[204]、美国 Cornell 大学[205]等单位开展了 DPA 技术研究。2016 年，德国耶拿大学在 8 路相干合成的基础上再进行了 4 脉冲分割放大，获得了平均功率为 700 W、脉冲能量为 12 mJ、脉冲宽度为 262 fs 的激光输出，合成效率为 78%[206]；2019 年，他们采用 12 路相干合成、8 脉冲分割放大，实现了 23 mJ 的飞秒脉冲输出[207]。奥地利维也纳理工大学[208]、美国密歇根大学[209]等单位采用吉莱-图努瓦干涉仪共振腔（GTI）的技术方案。美国密歇根大学于 2015 年验证了 5 个脉冲的 GTI 脉冲堆叠[209]，并于 2017 年实现了 81 个脉冲的堆叠，获得了 10 mJ 的脉冲能量[210]。德国耶拿大学开展了基于“堆叠-导出腔”（SnD，全称 stack-and-dump）的脉冲堆叠研究[9]，于 2016 年实现了 65 个脉冲的堆叠[211]。

相干光谱合成主要有两种技术方案，一是采用多个放大器对同一种子激光的不同谱段进行放大，再进行相干光谱合成，二是直接对多个锁模激光器进行相位锁定。采用第一种技术方案，2011 年，美国麻省理工学院对 2 路光参量啁啾脉冲放大器（OPCPA）进行了相干光谱合成，合成脉冲时间抖动小于 250 as[212]；2013 年，法国南巴黎大学实现了 2 路光纤放大器的相干光谱合成[213]，美国密歇根大学通过对 3 路光纤放大器进行相干光谱合成，使脉宽相对于合成前压窄了 1/2～1/3[214]，法国利摩日大学通过 12 芯光纤放大器的相干光谱合成，使脉冲宽度仅从种子激光的 228 fs 展宽到放大后的 280 fs[215]；2014 年，德国电子同步加速器研究所（DESY）通过对三路光参量放大器（OPA）的相干光谱合成，获得了脉冲宽度 1.9 fs 的超短脉冲激光[216]。采用第二种技术方案，2012 年，美国麻省理工学院通过对一路 Ti:蓝宝石激光器和一路光纤超连续谱激光器进行相干光谱合成，获得了 3.7 fs 的超短脉冲激光[217]；2016 年，天津大学实现了对两台飞秒激光器的脉冲序列与载波包络相位同步[218]，两路激光相干光谱合成后的光谱干涉图对比度约为 58%[219]。值得注意的是，近年来固体介质（如薄片）的超快激光技术也取得了迅速进展，若与相干合成技术结合，有望进一步提升系统效能。

4.5　变频激光相干合成

变频激光相干合成是获得特殊波长或者极端光场的有效技术途径，目前已有来自美国、俄罗斯、法国、中国等多个国家的科研人员开展相关研究工作[220-223]。俄罗斯规划用于极端光学研究的艾瓦中心（XCELS）拟实现 200 PW 峰值功率，待建激光装置包含 12 束功率为 15 PW、脉冲宽度为 25 fs 超强激光，利用相干合成技术来输出 200 PW 强光[10]。2014 年，科研人员实现了 2 路激光相干合成，实验结构和实验结果图11所示[197]，通过2束变频激光

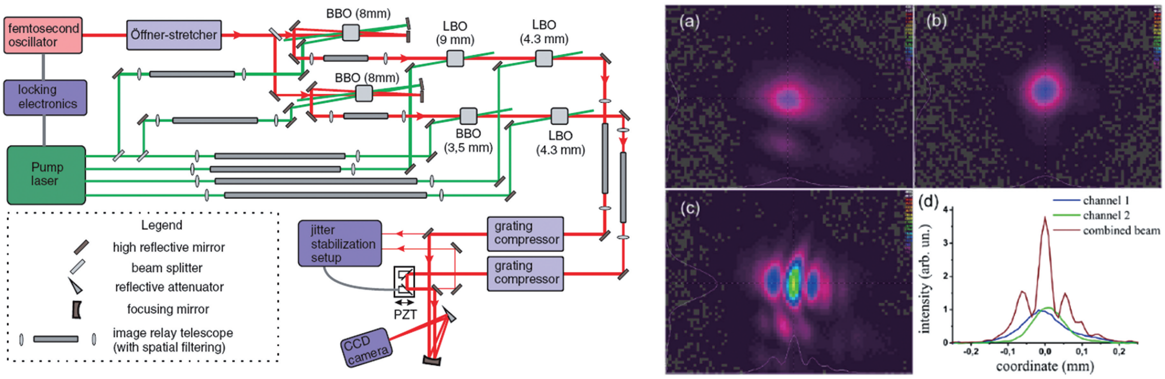

图 11　两束变频激光的相干合成实验结构和实验结果[197]

Fig. 11　Experimental setup and results of coherent beam combining of two variable frequency lasers[197]

的相干合成获得了 100 mJ 脉冲能量、23 fs 脉宽的强激光输出，合成效率达 95%。同年，法国科研人员报道了通过基频光相位控制实现变频光相干合成的实验结果[221]：实验中两束连续波 1.55 μm 的光纤激光通过周期极化铌酸锂(PPLN)晶体倍频至 775 nm，运用电光调制器(EOM)控制其中 1 束 1.55 μm 基频光的相位，实现了两路 775 nm 激光的相位控制，残差约为 λ/19.5。

5　应用领域不断拓展

5.1　非线性频率变换

非线性频率变换技术是实现高功率紫外、可见光、中红外等波段激光输出的典型技术手段[224-226]，相干合成技术是解决非线性频率变换系统泵浦亮度的重要技术途径。2017 年，立陶宛 Center for Physical Sciences & Technology 的科研人员报道了 4 路合成光纤激光在三硼酸钡(LBO)晶体中的频率上转换实验结果，获得了平均功率为 29 W 的 532 nm 激光输出[227-228]，转换效率为 51%。同年，日本 Osaka 大学的科研人员报道了基于相干合成光纤激光泵浦的高功率亚纳秒脉冲激光系统，实验结构如图 12 所示[229]；通过 8 束激光合成(2 套相干合成模块＋偏振合成)实现了千瓦级 1040 nm 基频脉冲激光输出，重复频率为 10 MHz、脉宽为 285 ps；经过频率变换系统，获得了平均功率为 600 W 的 520 nm 激光输出(二次谐波)和平均功率为 300 W 的 347 nm 激光输出(三次谐波)；对于 520 nm 激光和 347 nm 激光而言，上述平均功率都是非常先进的技术指标。

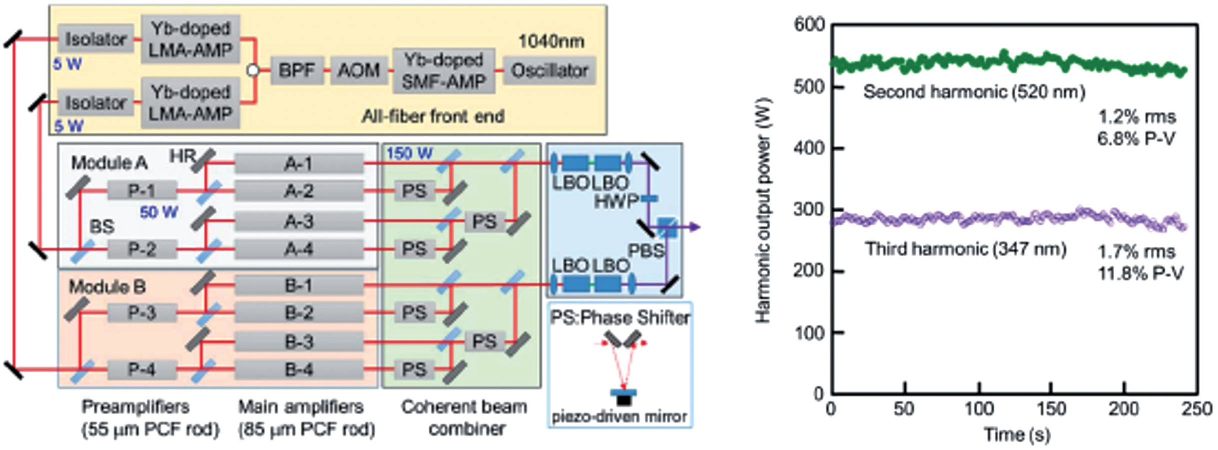

图 12　600 W 绿光和 300 W 紫外光产生系统的实验结构与输出功率[229]

Fig. 12　Experimental setup and output power for the 600 W green and 300 W ultraviolet light system[229]

2019 年，法国 Paris Saclay 大学等单位的科研人员报道了 3 束相干合成激光频率变换的结果[230]。通过 3 路锥形半导体激光放大器，实现了对 976 nm 单频激光的放大；再通过主动相位控制的方法实现 3 路激光相干合成，总输出功率为 12.9 W、输出功率大于 65%。相干合成光束通过周期极化 PPLN 晶体实现二次谐波变换，最终获得输出功率为 2 W 的 488 nm 激光输出。

5.2　雷达与导星

光纤激光具有热管理方便、结构紧凑等优势，是钠导星、激光雷达等应用领域的理想光源。但是，钠导星、相干雷达等需要激光具有较窄的线宽，由于受激布里渊散射等非线性效应的限制，单路光纤激光的功率通常难以满足应用需求。近年来，研究人员利用相干合成技术，将光纤激光的应用范围拓展到了这些领域。2010 年，欧洲南方天文台对 3 路 1178 nm 的单频拉曼放大器进行相干合成后再进行倍频，获得了 50 W 的 589 nm 钠黄光输出，成功应用于激光导星[231]。2013 年，美国罗切斯特大学成功将相干合成技术运用到多通道光纤慢光雷达系统中，使其具备了二维扫描能力[232]。2015 年，法国航空实验室对两路单频纳秒脉冲进行相干合成，将其应用到测风雷达系统中，使激光雷达的精度和量程都得到了大幅提升(图 13)[233]。

5.3　光场调控

近年来，随着激光技术的迅速发展，振幅、相位、偏振态及相干结构等具有特殊空间分布的结构光场相继提出，这些结构光场展现出新颖的物理效应和现象，拓展了激光技术的应用，在基础研究和工程应用等方面均引起了国内外研究人员的广泛关注，成为了光学与光电子学领域的研究热点[234-235]。新型的结构光场通过光场调控产生，主要包括：对光场的

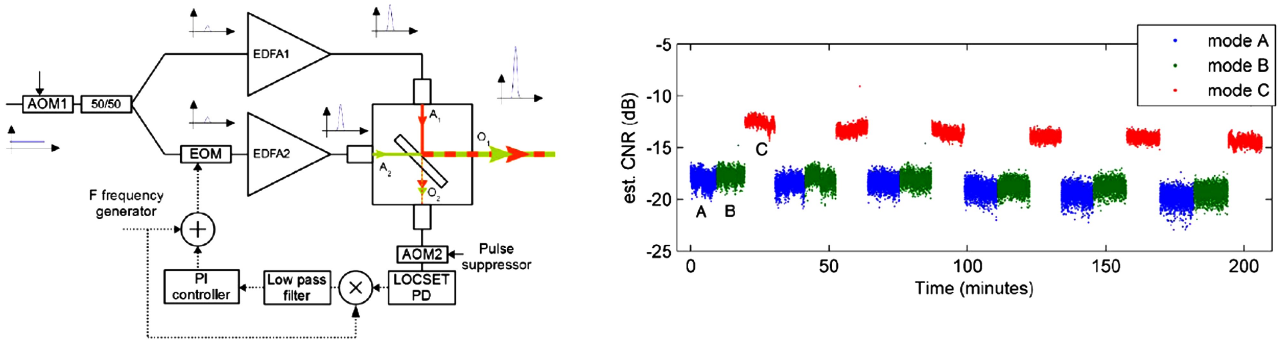

图 13　两路纳秒脉冲光纤激光相干合成的实验结构与实验结果[233]

Fig. 13　Experimental setup and result for coherent beam combining of two nanosecond pulsed fiber lasers [233]

相位空间分布进行调控,可以产生具有螺旋波前结构、携带轨道角动量(OAM)的涡旋光束;对光场的偏振态空间分布进行调控,可以产生具有奇异聚焦特性的矢量光束;对光场的振幅和相位空间分布进行联合调控,可以产生具有无衍射传输特性和自加速、自聚焦特性的艾里光束等。通过阵列光场调控是一种实现结构光场的重要方法[236],近年来取得了一系列重要进展,产生了涡旋光束、贝塞尔高斯光束、矢量光束和涡旋阵列光束等[237-244],并对大气传输特性进行了研究[245]。图 14(a)、(b)分别为阵列光束产生 OAM 光束的概念示意图,图 14(c)、(d)分别为 6 束激光产生 OAM 光束的实验结果。

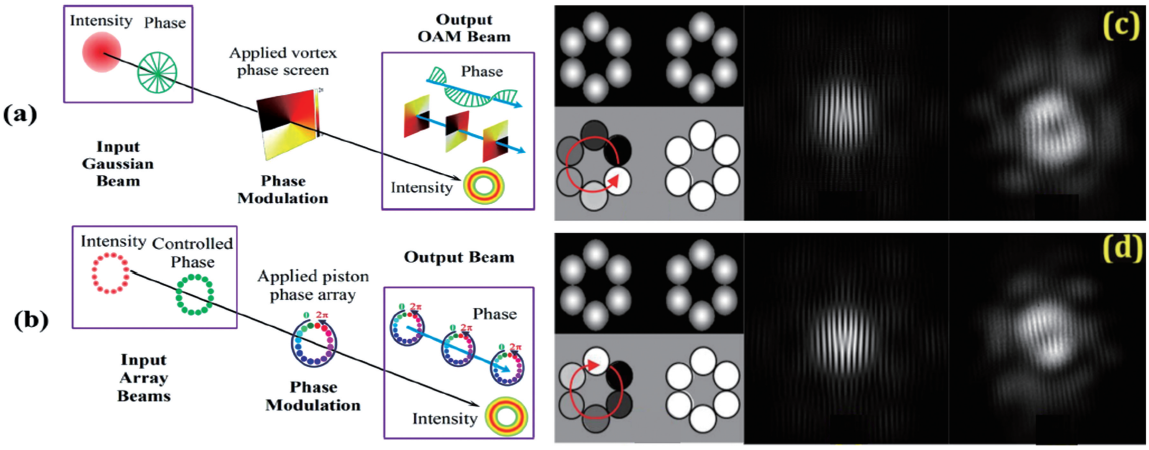

图 14　相干合成产生 OAM 光束的原理与实验结果[243]。(a)(b)阵列光束产生 OAM 光束的概念示意图;(c)(d) 6 束激光产生 OAM 光束的实验结果

Fig. 14　Principle and experimental results for producing OAM beams by coherent beam combining[243]. (a)(b) Schematic diagram of OAM beam produced by array beam; (c)(d) experimental results of OAM beam produced by 6 lasers

5.4　激光通信

相比传统的微波通信波段,激光波段频率高、波长短,具有载波频带宽、指向性好、抗电磁干扰能力强等优势,以及广阔的应用前景。但是,上述特点也给激光通信技术的发展带来一定挑战。

首先,大气湍流会对相干激光通信的性能产生影响。为了缓解大气湍流引起的深度衰减、探测效率下降,可以在接收望远镜中加入自适应光学系统。另一条有效的途径就是采用多口径接收,西班牙 Catalonia 大学[246-247]、美国林肯实验室[248-249]和中国科学院光电技术研究所[250-251]等单位开展了相关研究。多口径接收技术能在不增加单个接收望远镜口径的前提下提升总接收功率,还能通过数字合成[246-249]或者光学合成[250]的方式缓解大气湍流的影响。图 15 为中国科学院光电技术研究所研制的 7 单元阵列激光传输控制实验中激光发射端和回光接收端的实物照片[113]。

其次,需要配备高精度的跟瞄发射系统来实现激光发射。采用阵列光束相干合成发射是一条有效的技术途径,长春理工大学[252-253]、中国科学院光电技术研究所[251]等单位开展了相关研究。采用阵列光束发射具有许多优点:1)通过增加激光路数来增加发射功率,同时增加了空间传输距离;2)通过相位控制实现高精度、无机械式的光束扫描[252,254];3)通

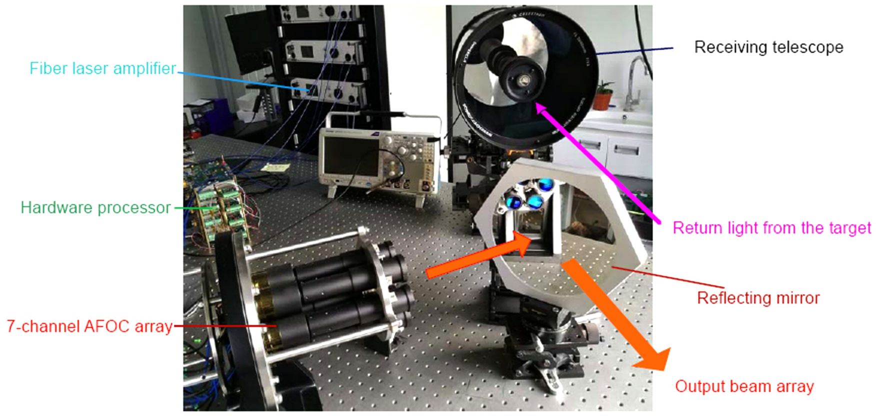

图 15　7 单元阵列激光传输控制实验中激光发射端和回光接收端的实物照片[113]

Fig. 15　Real photo of laser beam transmitter and receiver in the 7-channel laser-array transmission and control experiment[113]

过多载波调制[253]，增加了系统的传输效能。

5.5　大科学装置

激光发明 60 年来，研究人员不断追求着更高的激光亮度。强激光为人类提供了前所未有的实验手段和极端物理条件，激光大科学装置成为科学技术发展的重要标志[255]。随着国民经济和科学技术的发展，我国目前已经建成多个指标先进的激光大科学装置[256-260]。光纤激光以其高效率、易维护、可柔性操作等优点，在工业等领域得到广泛应用。近年来，基于光纤激光的大科学装置也受到广泛关注。例如，法国的研究人员为了应对 LIGO 对数百瓦低噪声单频激光的需求，演示了两路 40 W 单频光纤激光的长时间、低噪声相干合成实验，论证了基于光纤激光相干合成为 LIGO 提供光源的可行性[159]。

国际相干放大网络工程(简称 ICAN)是光纤激光大科学装置计划的典型代表。该计划由诺贝尔物理学奖获得者 Mourou 教授领导，其目标是对数以万计的超短脉冲进行相干合成，为下一代粒子加速器提供驱动源[8-9,261-264]，如图 16 所示。如此高功率的光源，在激光推进[265]、粒子束产生[266]、医疗[267]、原子能[268]、激光雷达和空间碎片清理[269]等方面也有广阔的应用前景。由于经费原因，目前启动了一个由巴黎综合理工学院牵头的 XCAN 项目，初步完成了 61 路光纤激光合成的技术验证实验[95,270]。

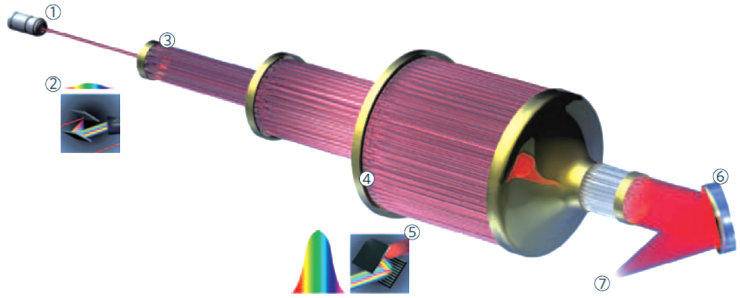

图 16　相干放大网络原理图[8]

Fig. 16　Principle of a coherent amplifier network[8]

6　结束语

相干合成是 21 世纪以来激光技术领域的研究前沿和热点。近 10 年来，随着可合成激光模块的性能提升和相干合成使能技术发展，激光相干合成领域取得了以 12 路 10.4 kW 超快光纤激光和 107 路大阵元数目光纤激光相干合成为典型代表的标志性成果，并在激光导星、激光雷达、激光变频等方面得到了成功应用，进一步推进了激光器及相关领域的技术进步。目前，在相干合成单元技术和连续光纤激光相干合成方面，国内外发展水平相当；对于超快激光、固体激光和半导体激光的相干合成，国内在系统指标方面与国外还存在一定差距。从发展趋势来看，全电驱动的可合成固态激光将继续向更高功率、更高效率、更轻重量和更小体积发展；相干合成技术将从阵元数目和单路激光功率等方面继续提升系统指标；且将拓展至任意增益介质和任意波段(可见光、中红外甚至太赫兹)的激光器，从而提升各种类

型激光系统的整体性能;此外,随着计算技术和计算能力的飞速进步,将人工智能相关技术引入相位控制、倾斜控制等相干合成使能技术部分,有望成量级地提升控制能力,使得大阵元多参量高速高精度控制变为可能,从而推动光频段的相控阵——激光相控阵逐步走向现实。

致谢 感谢博士研究生侯天悦、常琦对本文提出的意见建议。

参考文献

[1] Liu Z J, Zhou P, Wang X L, et al. The history, development and tend of coherent combining of laser beams[J]. Chinese Journal of Lasers, 2010, 37(9): 2221-2234.
刘泽金, 周朴, 王小林, 等. 激光相干合成的历史、现状与发展趋势[J]. 中国激光, 2010, 37(9): 2221-2234.

[2] McNaught S J, Asman C P, Injeyan H, et al. 100-kW coherently combined Nd∶YAG MOPA laser array[C]//Frontiers in Optics 2009, 2009: FThD2.

[3] Su R T, Zhou P, Zhang P F, et al. Review on the progress in coherent beam combining of ultra-short fiber lasers[J]. Infrared and Laser Engineering, 2018, 47(1): 0103001.
粟荣涛, 周朴, 张鹏飞, 等. 超短脉冲光纤激光相干合成[J]. 红外与激光工程, 2018, 47(1): 0103001.

[4] Brignon A. Coherent laser beam combining[M]. Weinheim: John Wiley & Sons Ltd., 2013.

[5] Liu Z J, Zhou P, Xu X J, et al. Coherent beam combining of high average power fiber lasers[M]. Beijing: National Defense Industry Press, 2016.
刘泽金, 周朴, 许晓军, 等. 高平均功率光纤激光相干合成[M]. 北京: 国防工业出版社, 2016.

[6] Cheng Y. Coherent combining of solid laser[M]. Beijing: Science Press, 2016.
程勇. 固体激光相干合成技术[M]. 北京: 科学出版社, 2016.

[7] Danson C N, Haefner C, Bromage J, et al. Petawatt and exawatt class lasers worldwide[J]. High Power Laser Science and Engineering, 2019, 7(3): 172-225.

[8] Mourou G, Brocklesby B, Tajima T, et al. The future is fibre accelerators[J]. Nature Photonics, 2013, 7(4): 258-261.

[9] Breitkopf S, Eidam T, Klenke A, et al. A concept for multiterawatt fibre lasers based on coherent pulse stacking in passive cavities[J]. Light: Science & Applications, 2014, 3(10): e211.

[10] Shaykin A, Kostyukov I, Sergeev A, et al. Prospects of PEARL 10 and XCELS laser facilities [J]. The Review of Laser Engineering, 2014, 42(2): 141.

[11] Kong H J, Park S, Cha S, et al. Conceptual design of the Kumgang laser: a high-power coherent beam combination laser using SC-SBS-PCMs towards a dream laser[J]. High Power Laser Science and Engineering, 2015, 3: e1.

[12] Liu Z J, Jin X X, Su R T, et al. Development status of high power fiber lasers and their coherent beam combination[J]. Science China Information Sciences, 2019, 62(4): 041301.

[13] Dawson J W, Messerly M J, Beach R J, et al. Analysis of the scalability of diffraction-limited fiber lasers and amplifiers to high average power[J]. Optics Express, 2008, 16(17): 13240-13266.

[14] Zhu J J, Zhou P, Ma Y X, et al. Power scaling analysis of tandem-pumped Yb-doped fiber lasers and amplifiers[J]. Optics Express, 2011, 19(19): 18645-18654.

[15] Otto H J, Jauregui C, Limpert J, et al. Average power limit of fiber-laser systems with nearly diffraction-limited beam quality[J]. Proceedings of SPIE, 2016, 9728: 97280E.

[16] Ke W W, Wang X J, Bao X F, et al. Thermally induced mode distortion and its limit to power scaling of fiber lasers[J]. Optics Express, 2013, 21(12): 14272-14281.

[17] Zervas M N. Transverse mode instability, thermal lensing and power scaling in Yb^{3+}-doped high-power fiber amplifiers[J]. Optics Express, 2019, 27(13): 19019-19041.

[18] Wang X L, Zhou P, Su R T, et al. Current situation, tendency and challenge of coherent combining of high power fiber lasers[J]. Chinese Journal of Lasers, 2017, 44(2): 0201001.
王小林, 周朴, 粟荣涛, 等. 高功率光纤激光相干合成的现状、趋势与挑战[J]. 中国激光, 2017, 44(2): 0201001.

[19] Liu Z J, Zhou P, Wang X L, et al. 9-channel fiber laser coherent synthesis kilowatt-level high power output[J]. Chinese Journal of Lasers, 2011, 38(1): 0102001-5.
刘泽金, 周朴, 王小林, 等. 9 路光纤激光相干合成千瓦级高功率输出[J]. 中国激光, 2011, 38(1): 0102001-5.

[20] Zhou P, Huang L J, Leng J Y, et al. High-power double-cladding fiber lasers: a 30-year overview[J]. Scientia Sinica (Technologica), 2020, 50(2): 123-135.
周朴, 黄良金, 冷进勇, 等. 高功率双包层光纤激光

器：30 周年的发展历程[J]. 中国科学：技术科学, 2020,50(2)：123-135.

[21] Lai W C, Ma P F, Ma P F, et al. 550 W single frequency fiber amplifiers emitting at 1030 nm based on a tapered Yb-doped fiber[J]. Optics Express, 2020, 28(14)：20908-20919.

[22] Zheng Y, Li P, Zhu Z D, et al. Progress in high-power narrow-linewidth fiber lasers[J]. Laser & Optoelectronics Progress, 2018,55(8)：080002.
郑也，李磐，朱占达，等. 高功率窄线宽光纤激光器研究进展[J]. 激光与光电子学进展, 2018,55(8)：080002.

[23] Lai W C, Ma P F, Xiao H, et al. High-power narrow-linewidth fiber laser technology[J]. High Power Laser and Particle Beams, 2020, 32(12)：121001.
来文昌，马鹏飞，肖虎，等. 高功率窄线宽光纤激光技术[J]. 强激光与粒子束, 2020,32(12)：121001.

[24] Wan P, Yang L M, Liu J. All fiber-based Yb-doped high energy, high power femtosecond fiber lasers[J]. Optics Express, 2013, 21(24)：29854-29859.

[25] IPG Photonics Corporation. YLS-ECO, 1–10 kW ytterbium CW laser systems [EB/OL]. [2020-10-03]. https://www.ipgphotonics.com/en/products/lasers/high-power-cw-fiber-lasers/1-micron/yls-eco-1-10-kw.

[26] IPG Photonics Corporation. The world's smallest kW-class fiber lasers [EB/OL]. [2020-10-03]. https://www.ipgphotonics.com/en/products/lasers/mid-power-cw-fiber-lasers/1-micron/ylr-u-series.

[27] Su R T, Zhou P, Wang X L, et al. Active coherent beam combination of two high-power single-frequency nanosecond fiber amplifiers[J]. Optics Letters, 2012, 37(4)：497-499.

[28] Su R T, Zhou P, Wang X L, et al. Active coherent beam combining of a five-element, 800 W nanosecond fiber amplifier array[J]. Optics Letters, 2012, 37(19)：3978-3980.

[29] Ma P F, Tao R M, Wang X L, et al. Coherent polarization beam combination of four mode-locked fiber MOPAs in picosecond regime[J]. Optics Express, 2014, 22(4)：4123-4130.

[30] Klenke A, Müller M, Stark H, et al. Coherent beam combination of ultrafast fiber lasers[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2018, 24(5)：1-9.

[31] Lombard L, Azarian A, Cadoret K, et al. Coherent beam combination of narrow-linewidth 1.5 μm fiber amplifiers in a long-pulse regime[J]. Optics Letters, 2011, 36(4)：523-525.

[32] Zhou P, Wang X L, Ma Y X, et al. Active and passive coherent beam combining of thulium-doped fiber lasers[J]. Proceedings of SPIE, 2010, 7843：784307.

[33] Goodno G D, Komine H, McNaught S J, et al. Coherent combination of high-power, zigzag slab lasers[J]. Optics Letters, 2006, 31(9)：1247-1249.

[34] Goodno G D, Asman C P, Anderegg J, et al. Brightness-scaling potential of actively phase-locked solid-state laser arrays[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2007, 13(3)：460-472.

[35] Marmo J, Injeyan H, Komine H, et al. Joint high power solid state laser program advancements at Northrop Grumman[J]. Proceedings of SPIE, 2009, 7195：719507.

[36] Gao Q S, Hu H, Pei Z P, et al. Design and experiment study of all-solid slab laser amplifier with laser power of 10 kW[J]. Chinese Journal of Lasers, 2012,39(2)：0202001.
高清松，胡浩，裴正平，等. 10 kW 级固体板条激光放大器设计与实验研究[J]. 中国激光, 2012,39(2)：0202001.

[37] Sun L C, Guo Y D, Shao C F, et al. 10.8 kW, 2.6 times diffraction limited laser based on a continuous wave Nd∶YAG oscillator and an extra-cavity adaptive optics system[J]. Optics Letters, 2018, 43(17)：4160-4163.

[38] Guo Y D, Peng Q J, Bo Y, et al. 24.6 kW near diffraction limit quasi-continuous-wave Nd∶YAG slab laser based on a stable-unstable hybrid cavity[J]. Optics Letters, 2020, 45(5)：1136-1139.

[39] Chen X M, Xu L, Hu H, et al. High-efficiency, high-average-power, CW Yb∶YAG zigzag slab master oscillator power amplifier at room temperature[J]. Optics Express, 2016, 24(21)：24517-24523.

[40] Wang D, Du Y L, Wu Y C, et al. 20 kW class high-beam-quality CW laser amplifier chain based on a Yb∶YAG slab at room temperature[J]. Optics Letters, 2018, 43(16)：3838-3841.

[41] Xu L, Wu Y C, Du Y L, et al. High brightness laser based on Yb∶YAG MOPA chain and adaptive optics system at room temperature[J]. Optics Express, 2018, 26(11)：14592-14600.

[42] Li M, Shang J L, Zhou T J, et al. Theoretical research on zero-phonon line pumped Yb∶YAG slab amplifier at room-temperature[J]. Acta Optica Sinica, 2019,39(2)：0214003.
李密，尚建力，周唐建，等. 室温下零声子线抽运 Yb∶YAG 板条放大器的理论研究[J]. 光学学报, 2019,39(2)：0214003.

[43] Huang L, Zheng Y M, Guo Y D, et al. 21.2 kW, 1.94 times diffraction-limit quasi-continuous-wave laser based on a multi-stage, power-scalable and adaptive optics controlled Yb∶YAG master-oscillator-power-amplifier system[J]. Chinese Optics Letters, 2020, 18(6): 061402.

[44] Ganija M, Ottaway D, Veitch P, et al. Cryogenic, high power, near diffraction limited, Yb∶YAG slab laser[J]. Optics Express, 2013, 21(6): 6973-6978.

[45] Lang X K, Jia P, Chen Y Y, et al. Advances in narrow linewidth diode lasers[J]. Scientia Sinica (Informationis), 2019, 49(6): 649-662.
郎兴凯，贾鹏，陈泳屹，等. 窄线宽半导体激光器研究进展[J]. 中国科学：信息科学，2019，49(6)：649-662.

[46] Chen L H, Yang G W, Liu Y X. Development of semiconductor lasers[J]. Chinese Journal of Lasers, 2020, 47(5): 0500001.
陈良惠，杨国文，刘育衔. 半导体激光器研究进展[J]. 中国激光，2020，47(5)：0500001.

[47] Zhang J, Chen Y Y, Qin L, et al. Advances in high power high beam quality diode lasers[J]. Chinese Science Bulletin, 2017, 62(32): 3719-3728.
张俊，陈泳屹，秦莉，等. 高功率、高光束质量半导体激光器研究进展[J]. 科学通报，2017，62(32)：3719-3728.

[48] Architecture for diode high energy laser systems (ADHELS)[EB/OL]. [2020-10-03]. http://www.mtosymposium.org/2007/posters/Energy/47_Mangano_ADHELS.pdf.

[49] Levy J L, Roh K. Coherent array of 900 semiconductor laser amplifiers[J]. Proceedings of SPIE, 1995, 2382: 58-69.

[50] Bachmann A, Lauer C, Furitsch M, et al. Recent brightness improvements of 976 nm high power laser bars[J]. Proceedings of SPIE, 2017, 1008: 1008602.

[51] Kanskar M, Bao L, Chen Z, et al. Continued improvement in reduced-mode (REM) diodes enable 272 W from 105 μm 0.15 NA beam[J]. Proceedings of SPIE, 2017, 1008: 1008609.

[52] Demir A, Peters M, Duesterberg R, et al. 29.5 W continuous wave output from 100 mm wide laser diode[J]. Proceedings of SPIE, 2015, 9348: 93480G.

[53] Kaifuchi Y, Yamagata Y, Nogawa R, et al. Ultimate high power operation of 9xx-nm single emitter broad stripe laser diodes[J]. Proceedings of SPIE, 2017, 1008: 100860D.

[54] Gapontsev V, Moshegov N, Berezin I, et al. Highly-efficient high-power pumps for fiber lasers[J]. Proceedings of SPIE, 2017, 1008: 1008604.

[55] Kaifuchi Y, Yoshida K, Yamagata Y, et al. Enhanced power conversion efficiency in 900-nm range single emitter broad stripe laser diodes maintaining high power operability[J]. Proceedings of SPIE, 2019, 1090: 109000F.

[56] Huang R K, Chann B, Burgess J, et al. Teradiode's high brightness semiconductor lasers[J]. Proceedings of SPIE, 2016, 9730: 97300C.

[57] Huang R K, Chann B, Glenn J D. Ultra-high brightness wavelength-stabilized kW-class fiber coupled diode laser[J]. Proceedings of SPIE, 2011, 7918: 791810.

[58] Bochove E J, Shakir S A. Analysis of a spatial-filtering passive fiber laser beam combining system[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2009, 15(2): 320-327.

[59] Yang Y F, Liu H K, Zheng Y, et al. Dammann-grating-based passive phase locking by an all-optical feedback loop[J]. Optics Letters, 2014, 39(3): 708-710.

[60] Cheng Y, Liu X, Liu Y, et al. Coherent characteristics of solid-state lasers with corner cubes[J]. Applied Optics, 2014, 53(15): 3267-3272.

[61] Li J F, Duan K L, Wang Y S, et al. High-power coherent beam combining of two photonic crystal fiber lasers[J]. IEEE Photonics Technology Letters, 2008, 20(11): 888-890.

[62] Corcoran C J, Durville F. Experimental demonstration of a phase-locked laser array using a self-Fourier cavity[J]. Applied Physics Letters, 2005, 86(20): 201118.

[63] Huo Y M, Cheo P K, King G G. Fundamental mode operation of a 19-core phase-locked Yb-doped fiber amplifier[J]. Optics Express, 2004, 12(25): 6230-6239.

[64] Michaille L, Taylor D M, Bennett C R, et al. Characteristics of a *Q*-switched multicore photonic crystal fiber laser with a very large mode field area[J]. Optics Letters, 2008, 33(1): 71-73.

[65] Bruesselbach H, Jones D C, Mangir M S, et al. Self-organized coherence in fiber laser arrays[J]. Optics Letters, 2005, 30(11): 1339-1341.

[66] Wang B S, Mies E, Minden M, et al. All-fiber 50 W coherently combined passive laser array[J]. Optics Letters, 2009, 34(7): 863-865.

[67] Zhou P, Wang X L, Ma Y X, et al. Stable coherent beam combination by active phasing a mutual injection-locked fiber laser array[J]. Optics Letters, 2010, 35(7): 950-952.

[68] Shardlow P C, Damzen M J. Phase conjugate self-

organized coherent beam combination: a passive technique for laser power scaling[J]. Optics Letters, 2010, 35(7): 1082-1084.

[69] Park S, Cha S, Oh J, et al. Coherent beam combination using self-phase locked stimulated Brillouin scattering phase conjugate mirrors with a rotating wedge for high power laser generation[J]. Optics Express, 2016, 24(8): 8641-8646.

[70] Zhou J, He B, Xue Y H, et al. Study on passive coherent beam combination technology of high power fiber laser arrays[J]. Acta Optica Sinica, 2011, 31(9): 0900129.
周军, 何兵, 薛宇豪, 等. 高功率光纤激光阵列被动相干组束技术研究[J]. 光学学报, 2011, 31(9): 0900129.

[71] Xiao R, Hou J, Liu M, et al. Coherent combining technology of master oscillator power amplifier fiber arrays[J]. Optics Express, 2008, 16(3): 2015-2022.

[72] Müller M, Klenke A, Stark H, et al. 16 channel coherently-combined ultrafast fiber laser [C] // Advanced Solid State Lasers 2017, 2017, AW4A.3.

[73] Klenke A, Seise E, Demmler S, et al. Coherently-combined two channel femtosecond fiber CPA system producing 3 mJ pulse energy[J]. Optics Express, 2011, 19(24): 24280-24285.

[74] Bourderionnet J, Bellanger C, Primot J, et al. Collective coherent phase combining of 64 fibers[J]. Optics Express, 2011, 19(18): 17053-17058.

[75] Antier M, Bourderionnet J, Larat C, et al. kHz closed loop interferometric technique for coherent fiber beam combining[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2014, 20(5): 182-187.

[76] Kabeya D, Kermene V, Fabert M, et al. Active coherent combining of laser beam arrays by means of phase-intensity mapping in an optimization loop[J]. Optics Express, 2015, 23(24): 31059-31068.

[77] Zhou P, Liu Z, Wang X, et al. Coherent beam combining of fiber amplifiers using stochastic parallel gradient descent algorithm and its application[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2009, 15(2):248-256.

[78] Yu C X, Augst S J, Redmond S M, et al. Coherent combining of a 4 kW, eight-element fiber amplifier array[J]. Optics Letters, 2011, 36(14): 2686-2688.

[79] Shay T M, Benham V, Baker J T, et al. Self-synchronous and self-referenced coherent beam combination for large optical arrays[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2007, 13(3): 480-486.

[80] McNaught S J, Thielen P A, Adams L N, et al. Scalable coherent combining of kilowatt fiber amplifiers into a 2.4-kW beam[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2014, 20(5): 174-181.

[81] Ma Y X, Zhou P, Wang X L, et al. Coherent beam combination with single frequency dithering technique[J]. Optics Letters, 2010, 35(9): 1308-1310.

[82] Su R T, Zhou P, Wang X L, et al. Phase locking of a coherent array of 32 fiber lasers[J]. High Power Laser and Particle Beams, 2014,26(11): 110101.
粟荣涛, 周朴, 王小林, 等. 32 路光纤激光相干阵列的相位锁定[J]. 强激光与粒子束, 2014, 26(11): 110101.

[83] Weyrauch T, Vorontsov M, Mangano J, et al. Deep turbulence effects mitigation with coherent combining of 21 laser beams over 7 km[J]. Optics Letters, 2016, 41(4): 840-843.

[84] Vorontsov M A, Weyrauch T. High-power lasers for directed-energy applications: comment[J]. Applied Optics, 2016, 55(35): 9950-9953.

[85] Su R, Xi J, Chang H, et al. Coherent combing of 60 fiber lasers using stochastic parallel gradient descent algorithm [C] // Applications of Lasers for Sensing and Free Space Communications 2019, 2019, JW2A.1.

[86] Ma P F, Ma Y X, Su R T, et al. High-quality and efficient coherent synthesis of 8 kW fiber laser[J]. Infrared and Laser Engineering, 2020, 49(5): 20190577.
马鹏飞, 马阎星, 粟荣涛, 等. 8 kW 级光纤激光优质高效相干合成[J]. 红外与激光工程, 2020, 49(5): 20190577.

[87] Chang H X, Chang Q, Hou T Y, et al. Coherent combining of hundred beams of fiber laser [J]. Chinese Journal of Lasers, 2020, 47(9): 0916002.
常洪祥, 常琦, 侯天悦, 等. 百束规模光纤激光相干合成[J]. 中国激光, 2020, 47(9): 0916002.

[88] Flores A. Coherent beam combining of fiber amplifiers in a kW regime[C]//Conference on Lasers and Electro-Optics, 2011.

[89] Flores A, Ehrehreich T, Holten R, et al. Multi-kW coherent combining of fiber lasers seeded with pseudo random phase modulated light [J]. Proceedings of SPIE, 2016, 9728: 97281Y.

[90] Müller M, Klenke A, Steinkopff A, et al. 3.5 kW coherently combined ultrafast fiber laser[J]. Optics Letters, 2018, 43(24): 6037-6040.

[91] Müller M, Aleshire C, Klenke A, et al. 10.4 kW coherently combined ultrafast fiber laser[J]. Optics Letters, 2020, 45(11): 3083-3086.

[92] Ma Y, Wang X, Leng J, et al. Coherent beam combination of 1.08 kW fiber amplifier array using single frequency dithering technique [J]. Optics Letters, 2011, 36(6): 951-953.

[93] Liu Z J, Zhou P, Ma P F, et al. 4 channels of high-power narrow linewidth, linear polarization fiber amplifiers coherent polarization synthesis to achieve 5 kW high-brightness laser output [J]. Chinese Journal of Lasers, 2017,44(4): 0415004.
刘泽金, 周朴, 马鹏飞, 等. 4 路高功率窄线宽、线偏振光纤放大器相干偏振合成实现 5 kW 级高亮度激光输出[J]. 中国激光, 2017,44(4): 0415004.

[94] Huang Z M, Tang X, Luo Y Q, et al. Active phase locking of thirty fiber channels using multilevel phase dithering method [J]. The Review of Scientific Instruments, 2016, 87(3): 033109.

[95] Fsaifes I, Daniault L, Bellanger S, et al. Coherent beam combining of 61 femtosecond fiber amplifiers [J]. Optics Express, 2020, 28(14): 20152-20161.

[96] Kabeya D, Kermène V, Fabert M, et al. Efficient phase-locking of 37 fiber amplifiers by phase-intensity mapping in an optimization loop[J]. Optics Express, 2017, 25(12): 13816-13821.

[97] Ma Y X, Zhou P, Wang X L, et al. Active phase locking of fiber amplifiers using sine-cosine single-frequency dithering technique[J]. Applied Optics, 2011, 50(19): 3330-3336.

[98] Azarian A, Bourdon P, Lombard L, et al. Orthogonal coding methods for increasing the number of multiplexed channels in coherent beam combining [J]. Applied Optics, 2014, 53(8): 1493-1502.

[99] Jiang M, Su R T, Zhang Z X, et al. Coherent beam combining of fiber lasers using a CDMA-based single-frequency dithering technique[J]. Applied Optics, 2017, 56(15): 4255-4260.

[100] Luo C, Su R T, Wang X L, et al. Adaptive stochastic parallel gradient descent algorithm and its application in coherent beam combining[J]. Acta Optica Sinica, 2014, 34(s1): s101006.
罗成, 粟荣涛, 王小林, 等. 自适应并行梯度随机下降算法及其在相干合成中的应用[J]. 光学学报, 2014, 34(s1): s101006.

[101] Hou T Y, An Y, Chang Q, et al. Deep-learning-based phase control method for tiled aperture coherent beam combining systems[J]. High Power Laser Science and Engineering, 2019, 7: e59.

[102] Chang Q, Su R T, Hou T Y, et al. Coherent beam combination based on particle swarm optimization algorithm [J]. Proceedings of SPIE, 2019, 1133: 1133319.

[103] Liu R Q, Peng C, Wu W S, et al. Coherent beam combination of multiple beams based on near-field angle modulation [J]. Optics Express, 2018, 26(2): 2045-2053.

[104] Liu R Q, Peng C, Liang X Y, et al. Coherent beam combination far-field measuring method based on amplitude modulation and deep learning[J]. Chinese Optics Letters, 2020, 18(4): 041402.

[105] Tünnermann H, Shirakawa A. Deep reinforcement learning for coherent beam combining applications [J]. Optics Express, 2019, 27(17): 24223-24230.

[106] Su R T, Zhou P, Wang X L, et al. High power narrow-linewidth nanosecond all-fiber lasers and their actively coherent beam combination[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2014, 20(5): 206-218.

[107] Su R T, Zhang Z X, Zhou P, et al. Coherent beam combining of a fiber lasers array based on cascaded phase control [J]. IEEE Photonics Technology Letters, 2016, 28(22): 2585-2588.

[108] Ahn H K, Kong H J. Cascaded multi-dithering theory for coherent beam combining of multiplexed beam elements[J]. Optics Express, 2015, 23(9): 12407-12413.

[109] Wang X, Wang X L, Zhou P, et al. 350-W coherent beam combining of fiber amplifiers with tilt-tip and phase-locking control [J]. IEEE Photonics Technology Letters, 2012, 24(19): 1781-1784.

[110] Beresnev L A, Vorontsov M A. Design of adaptive fiber optics collimator for free-space communication laser transceiver[J]. Proceedings of SPIE, 2005, 5895: 58950R.

[111] Weyrauch T, Vorontsov M A, Carhart G W, et al. Experimental demonstration of coherent beam combining over a 7 km propagation path[J]. Optics Letters, 2011, 36(22): 4455-4457.

[112] Geng C, Li X Y, Zhang X J, et al. Coherent beam combination of an optical array using adaptive fiber optics collimators [J]. Optics Communications, 2011, 284(24): 5531-5536.

[113] Geng C, Yang Y, Li F, et al. Research progress of fiber laser coherent combining[J]. Opto-Electronic Engineering, 2018,45(3): 170692.
耿超, 杨燕, 李枫, 等. 光纤激光相干合成研究进展[J]. 光电工程, 2018,45(3): 170692.

[114] Zhi D, Ma Y X, Ma P F, et al. Adaptive fiber optics collimator based on flexible hinges [J]. Applied Optics, 2014, 53(24): 5434-5438.

[115] Zhi D, Ma P F, Ma Y X, et al. Novel adaptive fiber-optics collimator for coherent beam combination[J]. Optics Express, 2014, 22(25): 31520-31528.

[116] Zhi D, Zhang Z X, Ma Y X, et al. Realization of large energy proportion in the central lobe by coherent beam combination based on conformal projection system[J]. Scientific Reports, 2017, 7: 2199.

[117] Le Dortz J, Heilmann A, Antier M, et al. Highly scalable femtosecond coherent beam combining demonstrated with 19 fibers[J]. Optics Letters, 2017, 42(10): 1887-1890.

[118] Geng C, Luo W, Tan Y, et al. Experimental demonstration of using divergence cost-function in SPGD algorithm for coherent beam combining with tip/tilt control[J]. Optics Express, 2013, 21(21): 25045-25055.

[119] Zhi D, Ma Y X, Ma P F, et al. Efficient coherent beam combining of fiber laser array through km-scale turbulent atmosphere[J]. Infrared and Laser Engineering, 2019,48(10): 1005007.
支冬, 马阎星, 马鹏飞, 等. 公里级湍流大气环境下光纤激光高效相干合成[J]. 红外与激光工程, 2019,48(10): 1005007.

[120] Yang Y, Geng C, Li F, et al. Coherent polarization beam combining approach based on polarization controlling in fiber devices[J]. IEEE Photonics Technology Letters, 2017, 29(12): 945-948.

[121] You Y, Qi Y F, He B, et al. Principles and development of active polarization control technology for fiber lasers[J]. Laser & Optoelectronics Progress, 2019,56(10): 100001.
尤阳, 漆云凤, 何兵, 等. 光纤激光主动偏振控制技术的原理与进展[J]. 激光与光电子学进展, 2019,56(10): 100001.

[122] Wang P, Shang Y P, Li X, et al. High efficient polarization-converting system based on combination of axicon and wave plate[J]. Chinese Journal of Lasers, 2015, 42(s1): s116002.
王鹏, 尚亚萍, 李霄, 等. 基于锥棱镜和波片组合实现的高效偏振转换系统[J]. 中国激光, 2015, 42(s1): s116002.

[123] Dong S H, Wang X L, Su R T, et al. Research on conversion technology from non-polarized to linearly polarized laser based on principle of polarization phase locking[J]. Chinese Journal of Lasers, 2016, 43(2): 0202006.
董苏惠, 王小林, 粟荣涛, 等. 基于偏振锁相的非线偏-线偏光转换技术研究[J]. 中国激光, 2016,43(2): 0202006.

[124] Shen H, Quan Z, Yang Y F, et al. Polarization control of combined laser beams based on optical homodyne polarization detection and phase locking[J]. Infrared and Laser Engineering, 2018,47(1): 0103007.
沈辉, 全昭, 杨依枫, 等. 基于光学零差偏振探测和锁相的合束激光偏振控制[J]. 红外与激光工程, 2018,47(1): 0103007.

[125] Wang D B, Zhou J F. Research on polarization control in the long distance fiber-optic sensing[J]. Proceedings of SPIE, 2013, 8914: 89141B.

[126] Xiong Y P, Su R T, Li X, et al. Adaptive polarization control of fiber amplifier based on SPGD algorithm[J]. Chinese Physics Letters, 2012, 29(12): 124212.

[127] Goodno G D, McNaught S J, Rothenberg J E, et al. Active phase and polarization locking of a 1.4 kW fiber amplifier[J]. Optics Letters, 2010, 35(10): 1542-1544.

[128] Wang Y S, Feng Y J, Wang X J, et al. 6.5 GHz linearly polarized kilowatt fiber amplifier based on active polarization control[J]. Applied Optics, 2017, 56(10): 2760-2765.

[129] Su R T, Liu Y K, Yang B L, et al. Active polarization control of a 1.43 kW narrow linewidth fiber amplifier based on SPGD algorithm[J]. Journal of Optics, 2017, 19(4): 045802.

[130] Goodno G D, McNaught S J, Weber M E, et al. Multichannel polarization stabilization for coherently combined fiber laser arrays[J]. Optics Letters, 2012, 37(20): 4272-4274.

[131] Xiong Y P, Su R T, Li X, et al. Coherent beam combining based on adaptive polarization and active phase control technique[J]. High Power Laser and Particle Beams, 2013,25(1): 5-6.
熊玉朋, 粟荣涛, 李霄, 等. 基于偏振自适应和主动相位控制的相干合成的实验研究[J]. 强激光与粒子束, 2013,25(1): 5-6.

[132] Goodno G D, Shih C C, Rothenberg J E. Perturbative analysis of coherent combining efficiency with mismatched lasers[J]. Optics Express, 2010, 18(24): 25403-25414.

[133] Benjamin Weiss S, Weber M E, Goodno G D. Group delay locking of coherently combined broadband lasers[J]. Optics Letters, 2012, 37(4): 455-457.

[134] Klenke A, Seise E, Limpert J, et al. Basic considerations on coherent combining of ultrashort laser pulses[J]. Optics Express, 2011, 19(25): 25379-25387.

[135] Su R T, Zhou P, Wang X L, et al. Impact of temporal and spectral aberrations on coherent beam combination of nanosecond fiber lasers[J]. Applied Optics, 2013, 52(10): 2187-2193.

[136] Yu H L, Ma P F, Wang X L, et al. Influence of

temporal-spectral effects on ultrafast fiber coherent polarization beam combining system [J]. Laser Physics Letters, 2015, 12(10): 105301.

[137] Seise E, Klenke A, Breitkopf S, et al. 88 W 0.5 mJ femtosecond laser pulses from two coherently combined fiber amplifiers[J]. Optics Letters, 2011, 36(19): 3858-3860.

[138] Yu H L, Zhang Z X, Wang X L, et al. High average power coherent femtosecond pulse combining system based on an all fiber active control method[J]. Laser Physics Letters, 2018, 15(7): 075101.

[139] Zhang Z X, Yu H L, Zhi D, et al. All fiber optical path difference adaptive control method in femtosecond fiber laser coherent polarization beam combination system[J]. Acta Optica Sinica, 2016, 36(9): 0906003.
张志新, 于海龙, 支冬, 等. 飞秒光纤激光相干偏振合成系统全光纤光程差自适应控制方法研究[J]. 光学学报, 2016,36(9): 0906003.

[140] Zhou P. Fundamentals of high-average-power fiber laser technology: mode[J]. High Power Laser and Particle Beams, 2018,30(6): 060201.
周朴. 高平均功率光纤激光技术基础: 模式[J]. 强激光与粒子束, 2018,30(6): 060201.

[141] Injeyan H, Goodno G, Palese S. High power laser handbook[M]. New York: McGraw-Hill, 2011.

[142] Ma P F. Study on coherent polarization beam combining system of high power fiber lasers[D]. Changsha: National University of Defense Technology, 2016.
马鹏飞. 高功率光纤激光相干偏振合成系统研究[D]. 长沙: 国防科学技术大学, 2016.

[143] Liu Z J, Ma P F, Su R T, et al. High-power coherent beam polarization combination of fiber lasers: progress and prospect [J]. Journal of the Optical Society of America B, 2017, 34(3): A7-A14.

[144] Tao R M, Wang X L, Zhou P. Comprehensive theoretical study of mode instability in high-power fiber lasers by employing a universal model and its implications[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2018, 24(3): 0903319.

[145] Jauregui C, Stihler C, Limpert J, et al. Transverse mode instability [J]. Advances in Optics and Photonics, 2020, 12(2): 429-484.

[146] Lei X, Wang S, Yan H, et al. Double-deformable-mirror adaptive optics system for laser beam cleanup using blind optimization[J]. Optics Express, 2012, 20(20): 22143-22157.

[147] Injeyan H, Goodno G, Komine H, et al. High power scalable Nd∶YAG laser architecture[C]// Conference on Lasers and Electro-Optics, 2005, May 22-27, 2005, Baltimore, MD, USA. New York: IEEE Press, 2005: CMJ3.

[148] Su R T, Yang B L, Xi X M, et al. 500 W level MOPA laser with switchable output modes based on active control[J]. Optics Express, 2017, 25(19): 23275-23282.

[149] Liu T, Chen S P, Qi X, et al. High-power transverse-mode-switchable all-fiber picosecond MOPA[J]. Optics Express, 2016, 24(24): 27821-27827.

[150] Song J X, Xu H Y, Wu H S, et al. High power narrow linewidth LP11 mode fiber laser using mode-selective FBGs[J]. Laser Physics Letters, 2018, 15(11): 115101.

[151] Song J X, Xu H Y, Wu H S, et al. All-fiberized transverse mode-switching method based on temperature control[J]. Applied Optics, 2019, 58(14): 3696-3702.

[152] Uberna R, Bratcher A, Alley T G, et al. Coherent combination of high power fiber amplifiers in a two-dimensional re-imaging waveguide [J]. Optics Express, 2010, 18(13): 13547-13553.

[153] Shekel E, Vidne Y, Urbach B. 16 kW single mode CW laser with dynamic beam for material processing [J]. Proceedings of SPIE, 2020, 1126: 1126021.

[154] Redmond S M, Ripin D J, Yu C X, et al. Diffractive coherent combining of a 2.5 kW fiber laser array into a 1.9 kW Gaussian beam[J]. Optics Letters, 2012, 37(14): 2832-2834.

[155] Ma P F, Zhou P, Su R T, et al. Coherent polarization beam combining of eight fiber lasers using single-frequency dithering technique[J]. Laser Physics Letters, 2012, 9(6): 456-458.

[156] Klenke A, Breitkopf S, Kienel M, et al. 530 W, 1.3 mJ, four-channel coherently combined femtosecond fiber chirped-pulse amplification system [J]. Optics Letters, 2013, 38(13): 2283-2285.

[157] Ma P F, Zhou P, Wang X L, et al. Coherent polarization beam combining of four 200-W-level fiber amplifiers[J]. Applied Physics Express, 2014, 7(2): 022703.

[158] Müller M, Kienel M, Klenke A, et al. 1 kW 1 mJ eight-channel ultrafast fiber laser [J]. Optics Letters, 2016, 41(15): 3439-3442.

[159] Wei L W, Cleva F, Man C N. Coherently combined master oscillator fiber power amplifiers for Advanced Virgo[J]. Optics Letters, 2016, 41(24): 5817-5820.

[160] Haraguchi E, Akiyama T, Ando T, et al. Simultaneous detection of beam pointing and optical

phase errors for multiple beams using a quadrant photo detector for high-efficiency coherent beam combining systems[J]. Applied Physics Express, 2019, 12(10): 102012.

[161] Bloom G, Larat C, Lallier E, et al. Coherent combining of two quantum-cascade lasers in a Michelson cavity[J]. Optics Letters, 2010, 35(11): 1917-1919.

[162] Bloom G, Larat C, Lallier E, et al. Passive coherent beam combining of quantum-cascade lasers with a Dammann grating[J]. Optics Letters, 2011, 36(19): 3810-3812.

[163] Redmond S M, Creedon K J, Kansky J E, et al. Active coherent beam combining of diode lasers[J]. Optics Letters, 2011, 36(6): 999-1001.

[164] Purnawirman, Phua P B. High power coherent polarization locked laser diode[J]. Optics Express, 2011, 19(6): 5364-5370.

[165] Zhao Y S, Zhu L. On-chip coherent combining of angled-grating diode lasers toward bar-scale single-mode lasers[J]. Optics Express, 2012, 20(6): 6375-6384.

[166] Creedon K J, Redmond S M, Smith G M, et al. High efficiency coherent beam combining of semiconductor optical amplifiers[J]. Optics Letters, 2012, 37(23): 5006-5008.

[167] Montoya J, Augst S J, Creedon K, et al. External cavity beam combining of 21 semiconductor lasers using SPGD[J]. Applied Optics, 2012, 51(11): 1724-1728.

[168] Zhao Y S, Zhu L. Improved beam quality of coherently combined angled-grating broad-area lasers[J]. IEEE Photonics Journal, 2013, 5(2): 1500307.

[169] Liu B, Braiman Y. Coherent beam combining of high power broad-area laser diode array with near diffraction limited beam quality and high power conversion efficiency[J]. Optics Express, 2013, 21(25): 31218-31228.

[170] Corcoran C J, Durville F. Passive coherent combination of a diode laser array with 35 elements[J]. Optics Express, 2014, 22(7): 8420-8425.

[171] Schimmel G, Doyen-Moldovan I, Janicot S, et al. Rear-side resonator architecture for the passive coherent combining of high-brightness laser diodes[J]. Optics Letters, 2016, 41(5): 950-953.

[172] Schimmel G, Janicot S, Hanna M, et al. Coherent beam combining architectures for high power tapered laser arrays[J]. Proceedings of SPIE, 2017, 1008: 100860O.

[173] Albrodt P, Niemeyer M, Crump P, et al. Coherent beam combining of high power quasi continuous wave tapered amplifiers[J]. Optics Express, 2019, 27(20): 27891-27901.

[174] Zhu H B, Duan X M, Fan S L, et al. Scalable structure of coherent polarization beam combining based on tapered diode laser amplifiers[J]. Optics & Laser Technology, 2020, 132: 106470.

[175] Huang Z, Tang X, Zhang D, et al. Phase locking of slab laser amplifiers via square wave dithering algorithm[J]. Applied Optics, 2014, 53(10): 2163-2169.

[176] Cheng Y, Liu X, Wan Q, et al. Mutual injection phase locking coherent combination of solid-state lasers based on corner cube[J]. Optics Letters, 2013, 38(23): 5150-5152.

[177] Kong H J, Park S, Cha S, et al. 4 kW coherent beam combination laser using self-controlled stimulated Brillouin scattering-phase conjugation mirrors for industrial applications[C] // Advanced Solid-State Lasers Congress, 2013: JTh2A.65.

[178] Kienel M, Müller M, Demmler S, et al. Coherent beam combination of Yb∶YAG single-crystal rod amplifiers[J]. Optics Letters, 2014, 39(11): 3278-3281.

[179] Peng C, Liang X Y, Liu R Q, et al. Two-beam coherent combining based on Ti: sapphire chirped-pulse amplification at the repetition of 1 Hz[J]. Optics Letters, 2019, 44(17): 4379-4382.

[180] Kong H J, Park S, Cha S, et al. Coherent beam combination laser system using SBS-PCM for high repetition rate solid-state lasers[J]. Optical Materials, 2013, 35(4): 807-811.

[181] Zhao P F, Dong Z Y, Zhang J Y, et al. Passive coherent beam combination of three Nd∶YAG lasers using cascaded Michelson-type compound cavities[J]. Optics Express, 2018, 26(14): 18019-18027.

[182] Liu J, Zeng Z N, Liang X Y, et al. Development trend of ultrafast and ultraintense lasers and their scientific application[J]. Strategic Study of Chinese Academy of Engineering, 2020,22(03), 22: 42-48.
刘军, 曾志男, 梁晓燕, 等. 超快超强激光及其科学应用发展趋势研究[J]. 中国工程科学, 2020,22(03), 22: 42-48.

[183] Fsaifes I, Daniault L, Bellanger S, et al. Coherent beam combining of 60 femtosecond fiber amplifiers[J]. Proceedings of SPIE, 2020, 11260: 112600L.

[184] Chang H, Chang Q, Hou T, et al. Coherent beam combining of 107 fiber lasers[C] // Advanced Solid State Lasers, 2020.

[185] Ma Y X, Zhou P, Wang X L, et al. Coherent beam

combination of two thulium-doped fiber laser beams with the multi-ditheringtechnique[J]. Optics & Laser Technology, 2011, 43(3): 721-724.

[186] Honzatko P, Baravets Y, Todorov F, et al. Coherently combined power of 20 W at 2000 nm from a pair of thulium-doped fiber lasers[J]. Laser Physics Letters, 2013, 10(9): 095104.

[187] Wang X, Zhou P, Wang X L, et al. 108 W coherent beam combining of two single-frequency Tm-doped fiber MOPAs[J]. Laser Physics Letters, 2014, 11(10): 105101.

[188] Gaida C, Kienel M, Müller M, et al. Coherent combination of two Tm-doped fiber amplifiers[J]. Optics Letters, 2015, 40(10): 2301-2304.

[189] Oermann M R, Carmody N, Hemming A, et al. Coherent beam combination of four holmium amplifiers with phase control via a direct digital synthesizer chip[J]. Optics Express, 2018, 26(6): 6715-6723.

[190] Wang X, Jin X X, Wu W J, et al. 310-W single frequency Tm-doped all-fiber MOPA[J]. IEEE Photonics Technology Letters, 2015, 27(6): 677-680.

[191] Hemming A, Simakov N, Davidson A, et al. A monolithic cladding pumped holmium-doped fibre laser[C]//CLEO: Science and Innovations, 2013, CW1M.1.

[192] Klenke A, Hädrich S, Eidam T, et al. 22 GW peak-power fiber chirped-pulse-amplification system[J]. Optics Letters, 2014, 39(24): 6875-6878.

[193] Heilmann A, le Dortz J, Daniault L, et al. Coherent beam combining of seven fiber chirped-pulse amplifiers using an interferometric phase measurement[J]. Optics Express, 2018, 26(24): 31542-31553.

[194] Daniault L, Hanna M, Lombard L, et al. Coherent beam combining of two femtosecond fiber chirped-pulse amplifiers[J]. Optics Letters, 2011, 36(5): 621-623.

[195] Siiman L A, Chang W Z, Zhou T, et al. Coherent femtosecond pulse combining of multiple parallel chirped pulse fiber amplifiers[J]. Optics Express, 2012, 20(16): 18097-18116.

[196] Bagayev S N, Leshchenko V E, Trunov V I, et al. Coherent combining of femtosecond pulses parametrically amplified in BBO crystals[J]. Optics Letters, 2014, 39(6): 1517-1520.

[197] Leshchenko V E, Trunov V I, Frolov S A, et al. Coherent combining of multimillijoule parametric-amplified femtosecond pulses[J]. Laser Physics Letters, 2014, 11(9): 095301.

[198] Yu H L. Study on high power femtosecond fiber lasers and their coherent beam combining technology[D]. Changsha: National University of Defense Technology, 2016.
于海龙. 高功率飞秒光纤激光及其相干合成技术研究[D]. 长沙: 国防科学技术大学, 2016.

[199] Yang K W, Zhu G S, Hao Q, et al. Coherent polarization beam combination by microcontroller-based phase-locking method[J]. IEEE Photonics Technology Letters, 2016, 28(20): 2129-2132.

[200] Mu J, Li Z L, Jing F, et al. Coherent combination of femtosecond pulses via non-collinear cross-correlation and far-field distribution[J]. Optics Letters, 2016, 41(2): 234-237.

[201] Peng C, Liang X Y, Liu R Q, et al. High-precision active synchronization control of high-power, tiled-aperture coherent beam combining[J]. Optics Letters, 2017, 42(19): 3960-3963.

[202] Hanna M, Guichard F, Zaouter Y, et al. Coherent combination of ultrafast fiber amplifiers[J]. Journal of Physics B: Atomic, Molecular and Optical Physics, 2016, 49(6): 062004.

[203] Limpert J, Klenke A, Kienel M, et al. Performance scaling of ultrafast laser systems by coherent addition of femtosecond pulses[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2014, 20(5): 268-277.

[204] Guichard F, Hanna M, Zaouter Y, et al. Analysis of limitations in divided-pulse nonlinear compression and amplification[J]. IEEE Journal of Selected Topics in Quantum Electronics, 2014, 20(5): 619-623.

[205] Lamb E S, Wright L G, Wise F W. Divided-pulse lasers[J]. Optics Letters, 2014, 39(9): 2775-2777.

[206] Kienel M, Müller M, Klenke A, et al. 12 mJ kW-class ultrafast fiber laser system using multidimensional coherent pulse addition[J]. Optics Letters, 2016, 41(14): 3343-3346.

[207] Stark H, Buldt J, Müller M, et al. 23 mJ high-power fiber CPA system using electro-optically controlled divided-pulse amplification[J]. Optics Letters, 2019, 44(22): 5529-5532.

[208] Astrauskas I, Kaksis E, Flöry T, et al. High-energy pulse stacking via regenerative pulse-burst amplification[J]. Optics Letters, 2017, 42(11): 2201-2204.

[209] Zhou T, Ruppe J, Zhu C, et al. Coherent pulse stacking amplification using low-finesse Gires-Tournois interferometers[J]. Optics Express, 2015, 23(6): 7442-7462.

[210] Pei H Z, Ruppe J, Chen S Y, et al. 10 mJ energy extraction from Yb-doped 85 μm core CCC fiber using coherent pulse stacking amplification of fs pulses[C]∥Advanced Solid State Lasers 2017, 2017, AW4A.4.

[211] Limpert J. Coherent temporal pulse-stacking approaches for peak-power scaling of ultrafast laser systems[C]∥High-Brightness Sources and Light-Driven Interactions, 2016, HM8B.1.

[212] Huang S W, Cirmi G, Moses J, et al. High-energy pulse synthesis with sub-cycle waveform control for strong-field physics[J]. Nature Photonics, 2011, 5(8): 475-479.

[213] Guichard F, Hanna M, Lombard L, et al. Two-channel pulse synthesis to overcome gain narrowing in femtosecond fiber amplifiers[J]. Optics Letters, 2013, 38(24): 5430-5433.

[214] Chang W Z, Zhou T, Siiman L A, et al. Femtosecond pulse spectral synthesis in coherently-spectrally combined multi-channel fiber chirped pulse amplifiers[J]. Optics Express, 2013, 21(3): 3897-3910.

[215] Rigaud P, Kermene V, Bouwmans G, et al. Spatially dispersive amplification in a 12-core fiber and femtosecond pulse synthesis by coherent spectral combining[J]. Optics Express, 2013, 21(11): 13555-13563.

[216] Chia S H, Cirmi G, Fang S B, et al. Two-octave-spanning dispersion-controlled precision optics for sub-optical-cycle waveform synthesizers[J]. Optica, 2014, 1(5): 315-322.

[217] Cox J A, Putnam W P, Sell A, et al. Pulse synthesis in the single-cycle regime from independent mode-locked lasers using attosecond-precision feedback[J]. Optics Letters, 2012, 37(17): 3579-3581.

[218] Tian H C, Song Y J, Ma C Y, et al. Timing and carrier envelope phase synchronization from two independent femtosecond lasers[J]. Chinese Journal of Lasers, 2016, 43(8): 0801003.
田昊晨, 宋有建, 马春阳, 等. 两台独立飞秒激光器的脉冲序列与载波包络相位同步[J]. 中国激光, 2016, 43(8): 0801003.

[219] Tian H C, Song Y J, Meng F, et al. Long-term stable coherent beam combination of independent femtosecond Yb-fiber lasers[J]. Optics Letters, 2016, 41(22): 5142-5145.

[220] Marandi A, Leindecker N C, Pervak V, et al. Coherence properties of a broadband femtosecond mid-IR optical parametric oscillator operating at degeneracy[J]. Optics Express, 2012, 20(7): 7255-7262.

[221] Durécu A, Canat G, Le Gouët J, et al. Coherent combining of SHG converters[C]∥CLEO: Applications and Technology 2014, 2014, JTh2A.19.

[222] Li X, Xiao H, Dong X L, et al. Coherent beam combining of two slab laser amplifiers and second-harmonic phase locking based on a multi-dithering technique[J]. Chinese Physics Letters, 2011, 28(9): 094210.

[223] Guan Y F, Zhang P Q, Xie X S, et al. Coherent beam combining with second-harmonic generation optimized with adaptive phase control[J]. IEEE Journal of Quantum Electronics, 2011, 47(3): 348-353.

[224] Gapontsev V, Avdokhin A, Kadwani P, et al. SM green fiber laser operating in CW and QCW regimes and producing over 550 W of average output power[J]. Proceedings of SPIE, 2014, 8964: 896407.

[225] Nikitin D G, Byalkovskiy O A, Vershinin O I, et al. Sum frequency generation of UV laser radiation at 266 nm in LBO crystal[J]. Optics Letters, 2016, 41(7): 1660-1663.

[226] Cole B, Goldberg L, Chinn S, et al. Compact and efficient mid-IR OPO source pumped by a passively *Q*-switched Tm: YAP laser[J]. Optics Letters, 2018, 43(5): 1099-1102.

[227] Želudevičius J, Regelskis K, Račiukaitis G. Experimental demonstration of pulse multiplexing and beam combining of four fiber lasers by noncollinear frequency conversion in an LBO crystal[J]. Optics Letters, 2017, 42(2): 175-178.

[228] Želudevičius J, Rutkauskas R, Regelskis K. Coherent beam combining of pulsed fiber amplifiers by noncolinear sum-frequency generation[J]. Optics Letters, 2019, 44(7): 1813-1816.

[229] Tsubakimoto K, Yoshida H, Miyanaga N. 600 W green and 300 W UV light generated from an eight-beam, sub-nanosecond fiber laser system[J]. Optics Letters, 2017, 42(17): 3255-3258.

[230] Albrodt P, Jamal M T, Hansen A K, et al. Coherent combining of high brightness tapered amplifiers for efficient non-linear conversion[J]. Optics Express, 2019, 27(2): 928-937.

[231] Taylor L R, Feng Y, Calia D B. 50W CW visible laser source at 589 nm obtained via frequency doubling of three coherently combined narrow-band Raman fibre amplifiers[J]. Optics Express, 2010, 18(8): 8540-8555.

[232] Vornehm J E, Schweinsberg A, Shi Z, et al. Phase locking of multiple optical fiber channels for a slow-

light-enabled laser radar system [J]. Optics Express, 2013, 21(11): 13094-13104.

[233] Lombard L, Valla M, Planchat C, et al. Eyesafe coherent detection wind lidar based on a beam-combined pulsed laser source[J]. Optics Letters, 2015, 40(6): 1030-1033.

[234] Zhao J L, Cai Y J. Introduction for feature issue on light field, control, transmission, and application [J]. Acta Optica Sinica, 2016, 36 (10), 36: 1026000.
赵建林, 蔡阳健. “光场调控、传输及其应用”专题前言[J]. 光学学报, 2016,36(10), 36: 1026000.

[235] Zhao J L, Cai Y J. Introduction for feature issue on light field manipulation, transmission, and application (section II) [J]. Acta Optica Sinica, 2019, 39(1): 0126000.
赵建林,蔡阳健. “光场调控、传输及其应用”专题Ⅱ前言[J]. 光学学报,2019,39(1):0126000.

[236] Hou T Y, Zhou P, Ma Y X, et al. Review on structured optical field generated from array beams [J]. Proceedings of SPIE, 2018, 1071: 107103Z.

[237] Ma P F, Zhou P, Ma Y X, et al. Generation of azimuthally and radially polarized beams by coherent polarization beam combination[J]. Optics Letters, 2012, 37(13): 2658-2660.

[238] Aksenov V P, Dudorov V V, Kolosov V V. Properties of vortex beams formed by an array of fibre lasers and their propagation in a turbulent atmosphere[J]. Quantum Electronics, 2016, 46 (8): 726-732.

[239] Aksenov V P, Dudorov V V, Filimonov G A, et al. Vortex beams with zero orbital angular momentum and non-zero topological charge[J]. Optics & Laser Technology, 2018, 104: 159-163.

[240] Hou T Y, Zhi D, Tao R M, et al. Spatially-distributed orbital angular momentum beam array generation based on greedy algorithms and coherent combining technology[J]. Optics Express, 2018, 26 (12): 14945-14958.

[241] Hou T Y, Zhang Y Q, Chang Q, et al. High-power vortex beam generation enabled by a phased beam array fed at the nonfocal-plane[J]. Optics Express, 2019, 27(4): 4046-4059.

[242] Hou T Y, An Y, Chang Q, et al. Deep-learning-assisted, two-stage phase control method for high-power mode-programmable orbital angular momentum beam generation [J]. Photonics Research, 2020, 8(5): 715-722.

[243] Zhi D, Hou T Y, Ma P F, et al. Comprehensive investigation on producing high-power orbital angular momentum beams by coherent combining technology[J]. High Power Laser Science and Engineering, 2019,7(2): e33.

[244] Yu T, Xia H, Xie W K, et al. The generation and verification of Bessel-Gaussian beam based on coherent beam combining[J]. Results in Physics, 2020, 16: 102872.

[245] Aksenov V P, Dudorov V V, Kolosov V V, et al. Synthesized vortex beams in the turbulent atmosphere[J]. Frontiers in Physics, 2020, 8: 143.

[246] Belmonte A. Digital equalization of time-delay array receivers on coherent laser communications [J]. Optics Letters, 2017, 42(2): 310-313.

[247] Belmonte A. Capacity of coherent laser downlinks [J]. Journal of Lightwave Technology, 2014, 32 (11): 2128-2132.

[248] Geisler D J, Yarnall T M, Schieler C M, et al. Experimental demonstration of multi-aperture digital coherent combining over a 3.2-km free-space link [J]. Proceedings of SPIE, 2017, 1009: 100960C.

[249] Geisler D J, Yarnall T M, Stevens M L, et al. Multi-aperture digital coherent combining for free-space optical communication receivers[J]. Optics Express, 2016, 24(12): 12661-12671.

[250] Yang Y, Geng C, Li F, et al. Multi-aperture all-fiber active coherent beam combining for free-space optical communication receivers [J]. Optics Express, 2017, 25(22): 27519-27532.

[251] Geng C, Geng C, Li F, et al. Fiber laser transceiving and wavefront aberration mitigation with adaptive distributed aperture array for free-space optical communications[J]. Optics Letters, 2020, 45(7): 1906-1909.

[252] Han J, Chen H, Ma W Z, et al. Research on communication based on optical fiber laser phased array technology [J]. Electro-Optic Technology Application, 2015,30(2): 74-77.
韩建, 陈恒, 马万卓, 等. 光纤激光相控阵技术的通信研究[J]. 光电技术应用, 2015,30(2): 74-77.

[253] Bi M Z, Su Y W, Ma W Z, et al. Space laser communication system based on fiber laser phased array[J]. Journal of Applied Optics, 2016,37(6): 938-941.
毕明喆, 苏煜炜, 马万卓, 等. 基于光纤激光相控阵的空间激光通信系统[J]. 应用光学, 2016,37 (6): 938-941.

[254] Sun H W, Han J, Ci M R, et al. Research of high-power fiber laser phased array communications technology[J]. Optical Communication Technology, 2015,39(1): 36-38.
孙鸿伟, 韩建, 慈明儒, 等. 大功率光纤激光相控通信技术研究[J]. 光通信技术, 2015,39(1): 36-

38.

[255] Moses E I. The national ignition facility and the promise of inertial fusion energy[J]. Fusion Science and Technology, 2011, 60(1): 11-16.

[256] Leng Y X. Shanghai superintense ultrafast laser facility[J]. Chinese Journal of Lasers, 2019,46(1): 0100001.
冷雨欣. 上海超强超短激光实验装置[J]. 中国激光, 2019,46(1): 0100001.

[257] Zhu J Q, Chen S H, Zheng Y X, et al. Review on development of Shenguang-Ⅱ laser facility [J]. Chinese Journal of Lasers, 2019,46(1): 0100002.
朱健强, 陈绍和, 郑玉霞, 等. 神光Ⅱ激光装置研制[J]. 中国激光, 2019,46(1): 0100002.

[258] Zhang X M, Wei X F. Review of new generation of huge-scale high peak power laser facility in China [J]. Chinese Journal of Lasers, 2019, 46(1): 0100003.
张小民, 魏晓峰. 中国新一代巨型高峰值功率激光装置发展回顾[J]. 中国激光, 2019, 46(1): 0100003.

[259] Zhao Z T, Wang D, Yin L X, et al. Shanghai soft X-ray free-electron laser facility[J]. Chinese Journal of Lasers, 2019,46(1): 0100004.
赵振堂, 王东, 殷立新, 等. 上海软 X 射线自由电子激光装置[J]. 中国激光, 2019,46(1): 0100004.

[260] Yu Y, Li Q M, Yang J Y, et al. Dalian extreme ultraviolet coherent light source[J]. Chinese Journal of Lasers, 2019,46(1): 0100005.
余永, 李钦明, 杨家岳, 等. 大连极紫外相干光源[J]. 中国激光, 2019,46(1): 0100005.

[261] Soulard R, Quinn M N, Mourou G. Design and properties of a coherent amplifying network laser [J]. Applied Optics, 2015, 54(15): 4640-4645.

[262] Mourou G. Science and applications of the coherent amplifying network (CAN) laser[J]. The European Physical Journal Special Topics, 2015, 224(13): 2527-2528.

[263] Luu-Thanh P, Tuckmantel T, Pukhov A, et al. Laser fields in dynamically ionized plasma structures for coherent acceleration[J]. The European Physical Journal Special Topics, 2015, 224(13): 2625-2629.

[264] Holzer B J. CERN needs for future accelerators in high energy physics [J]. The European Physical Journal Special Topics, 2015, 224(13): 2615-2620.

[265] Roth M, Logan B G. Advanced space power and propulsion based on lasers [J]. The European Physical Journal Special Topics, 2015, 224(13): 2657-2663.

[266] Moustaizis S D, Lalousis P, Perrakis K, et al. ICAN: high power neutral beam generation[J]. The European Physical Journal Special Topics, 2015, 224(13): 2639-2643.

[267] Bychenkov V Y, Brantov A V. Laser-based ion sources for medical applications[J]. The European Physical Journal Special Topics, 2015, 224(13): 2621-2624.

[268] Gales S, Team F T E N. Laser driven nuclear science and applications: the need of high efficiency, high power and high repetition rate Laser beams[J]. The European Physical Journal Special Topics, 2015, 224(13): 2631-2637.

[269] Quinn M N, Jukna V, Ebisuzaki T, et al. Space-based application of the CAN laser to LIDAR and orbital debris remediation [J]. The European Physical Journal Special Topics, 2015, 224(13): 2645-2655.

[270] Daniault L, Bellanger S, Le Dortz J, et al. XCAN: a coherent amplification network of femtosecond fiber chirped-pulse amplifiers [J]. The European Physical Journal Special Topics, 2015, 224(13): 2609-2613.

Review of Coherent Laser Beam Combining Research Progress in the Past Decade

Zhou Pu*, Su Rongtao, Ma Yanxing, Ma Pengfei, Wu Jian, Li Can, Jiang Man
College of Advanced Interdisciplinary Studies, *National University of Defense Technology*, *Changsha*, *Hunan* 410073, *China*

Abstract

Significance Coherent beam combining (CBC) of lasers is an effective technical approach for scaling the power of a laser while maintaining good beam quality. In 2009, Northrop Grumman Aerospace Systems demonstrated the world's first 100 kW solid-state laser system, in which seven 15 kW master oscillator-power amplifier laser chains were coherently combined. It was an important milestone in the history of laser development. In the past 10 years

(2011—2020), CBC has developed rapidly, and many representative results have been produced. In this paper, the research progress of coherent laser beam combining in the past decade is reviewed.

Progress First, the output power of fiber, solid-state, and semiconductor lasers has increased significantly, which has provided high-power combinable laser elements for CBC systems. For example, the output power levels of single-frequency and narrow-line-width fiber lasers have reached 500 W and 4 kW, respectively; the average power of femtosecond fiber lasers has exceeded 1 kW; and Nd∶YAG and Yb∶YAG solid-state lasers have both generated over 20 kW in output power.

Second, enabling technologies for coherent laser beam combining have been developed, including phase control, tip-tilt control, polarization control, optical path difference control, high-order aberration control, and aperture-filling. More than 100 fiber lasers have been phase-locked based on active phase control technology. High-power adaptive fiber optic collimators have been designed that can be used for tip-tilt control of fiber lasers with kilowatt-level output power. Active polarization control of a kilowatt-level fiber amplifier has been realized, which has been employed to increase the combination efficiency of CBC systems. High-precision optical path difference real-time control systems have been designed and used for CBC of broad-spectrum and ultrafast lasers. Mode control technologies and adaptive optics methods have been employed for flexible mode manipulation. Aperture-filling technologies, such as microlens arrays, diffractive optical elements, and polarization beam combiners, have also been developed to increase efficiency of combination.

Third, representative results of the coherent combining of various kinds of lasers have been produced. For semiconductor lasers, coherent combining of 218 elements, with total output power of 38.5 W, has been realized. For solid-state lasers, pulse energy of 15.3 J has been obtained by the coherent combing of 6 solid-state lasers, and peak power of 3.7 GW has been obtained by the coherent combining of 2 ultrafast Yb∶YAG lasers. For fiber lasers, the number of laser channels has been increased to 107, and 16-kW output power has been obtained by the coherent combining of 32 fiber lasers. For ultrafast lasers, 61-fs fiber lasers have been coherently combined, and 10.4 kW average power has been generated by the coherent combining of 12 fs fiber lasers. In order to increase pulse energy, divided-pulse amplification and coherent temporal pulse-stacking technologies have been developed. Based on divided-pulse amplification, femtosecond pulses with energy of 23 mJ have been generated; using temporal pulse-stacking technology, 81 pulses were coherently combined to be one pulse with 10 mJ energy.

Fourth, coherent laser beam combining has been employed in versatile applications. For nonlinear frequency conversion applications, high pump brightness is required. A 600 W, 520 nm laser (second harmonic) and a 300 W, 347 nm laser (third harmonic) were obtained based on 1040 nm with kilowatt output power generated through a CBC system. Similarly, by coherently combining narrow-line-width lasers, sufficient output power was obtained for applications such as laser guide star and laser radar. By controlling the optical parameters of a coherent laser array, structural light fields with special spatial distribution can be obtained, such as vortex beams carrying orbital angular momentum. In recent years, research plans for large scientific facilities based on coherent laser beam combining have been proposed. For example, LIGO needs a low-noise single-frequency laser with hundreds of watts of output power; researchers have demonstrated the feasibility of obtaining such a laser source through coherent combining of fiber lasers. The International Coherent Amplification Network project has been proposed to provide a laser source for the next generation of particle accelerators.

Prospects In future work, increasing the number of coherent laser array elements and scaling the power of single-channel lasers will still be the development tendency. Lasers can be extended to almost arbitrary gain medium and wavelength band (visible light, mid-infrared, and even terahertz). Moreover, with the rapid development of computing technology and computational power, artificial intelligence techniques may be used for CBC-enabling technologies such as phase control and tip-tilt control. In the case of multiple-parameter control for massive laser arrays, high-power laser phased arrays will be realized.

Key words lasers; coherent beam combining; high energy laser; fiber laser; solid state laser; diode laser

OCIS codes 140.3290; 140.3510; 140.3298