中国激光

高平均功率光纤激光的研究进展与发展趋势

周朴*，冷进勇，肖虎，马鹏飞，许将明，刘伟，姚天甫，张汉伟，黄良金，潘志勇

国防科技大学前沿交叉学科学院，湖南 长沙 410073

摘要 简要回顾了高功率光纤激光的发展历程，以高功率光纤激光的“代表作”——万瓦级单模光纤激光为例，深入剖析了结构和参数特征。随后从该激光器的特征出发，从泵浦方式、系统结构、激光波长、激光线宽和脉冲机制等多个角度，梳理总结了高功率光纤激光领域取得的技术突破和重要进展。最后结合高功率光纤激光领域发展呈现的若干主要特征，对高平均功率光纤激光的发展趋势进行了初步研判。

关键词 光纤光学；高功率激光；泵浦；结构；波长；拉曼；线宽；脉冲

中图分类号 O436 **文献标志码** A **doi**：10.3788/CJL202148.2000001

1 引 言

高平均功率光纤激光具有结构紧凑、电光效率高、可柔性操作等特点，在先进制造、能源勘探、国家安全等领域都有重要的应用[1-4]。1988 年双包层光纤的发明[5]，改变了早期光纤激光器只是一种中低功率光子器件的历史。此后，伴随着光纤制备和半导体激光等技术的进步，光纤激光的输出功率得到了迅速提升。2004 年是高功率光纤激光发展史上的重要年份：英国南安普顿大学和德国耶拿大学采用空间光学结构实现了单纤千瓦级高功率高光束质量输出[6-7]，美国 IPG Photonics 公司采用全光纤结构实现了类似结果[8]。此后，高光束质量单纤激光输出功率在 5 年内实现了从千瓦到万瓦的飞跃，其间几乎所有重要突破都是由 IPG Photonics 公司实现的。2009 年，IPG Photonics 公司公布单纤单模激光输出功率超过 9.6 kW[9]；2010 年，该公司在 Laser Optics 会议上公布单纤单模激光输出功率达 10.5 kW[10]。上述两个代表性结果是光纤激光领域的里程碑，此后，除 IPG Photonics 公司在 2013 年的 CLEO 会议上发布了单纤单模激光 20 kW 输出的消息外[11]，没有进一步输出功率提升的相关报道。从文献分析结果看，近年来国内外其他单位一直在朝着单纤单模 10 kW 输出的目标努力，但是仍然没有第二家单位实现单纤单模光纤激光输出。与此同时，近年来 10 kW 级(以上)近单模固体激光的研究报道不断涌现[12-14]。从表面上看，高平均功率光纤激光技术领域已经多年没有重要技术突破或进展；实际上，近十年是高平均功率光纤激光的“黄金时期”，在物理机制、器件工艺等基础研究突破的基础上，多种波段、多种体制的光纤激光都得到了飞速发展，并从实验室走向了大规模应用。本文选取高平均功率光纤激光为研究对象，从 IPG Photonics 公司 2010 年前后实现的 10 kW 单纤单模激光器的结构和输出参数出发，围绕高平均功率光纤激光的泵浦方式、系统结构、增益介质、激光线宽和时序特性等特征，全面梳理了高平均功率光纤激光技术领域的研究进展，旨在呈现近年来相关领域的发展全貌，并根据当前的态势和技术动向，对高平均功率光纤激光的发展趋势进行了简要分析与预测。

2 10 kW 单模光纤激光的实现历程与参数分析

采用与增益光纤吸收波段匹配的半导体激光作为泵浦源，是实现高功率光纤激光输出的通用泵浦方式[15]。回顾高功率单模光纤激光的发展历程不难发现，很多文献的标题或正文里提到“pump limited”，意思是如果有充足的泵浦能力，激光器的输出功率可以

收稿日期：2021-04-06；**修回日期**：2021-06-18；**录用日期**：2021-06-29

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)

通信作者：*zhoupu203@163.com

得到进一步的提高。以文献[16]报道的 2 kW 级光纤激光为例，如图 1 所示：该激光系统结构以一个 500 W 级的激光器作为种子，经过一级功率放大(到 1 kW 级)和二级功率放大后实现 2 kW 级功率输出。

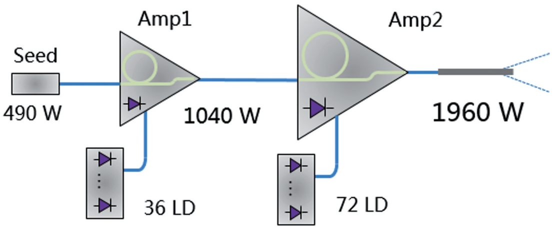

图 1　2005 年报道的 2 kW 级光纤激光系统结构[16]

Fig. 1　Structural diagram of 2 kW-level fiber laser system reported in 2005[16]

从目前的技术发展水平来看，50 W 级的种子激光经过一级放大就可以实现 2 kW 级功率输出[17]，可在当时(2005 年)，泵浦源的亮度是难以支持一级放大技术方案的。此外，2010 年报道的 2 μm 波段千瓦级掺铥光纤激光也是采用了二级放大的方案[18]；2021 年初报道的窄线宽千瓦级掺铥光纤激光虽然系统结构较为复杂，但从十瓦级到千瓦级的放大只需一级就实现了[19]。

基于半导体激光泵浦的光纤激光在 2004 年首次实现了千瓦级功率输出，在 2007 年实现了 3.5 kW 级功率输出[20]，此后泵浦源亮度的发展似乎跟不上激光器输出功率提升的速度。因此，级联泵浦技术被提出并被应用到高功率光纤激光上来[21-22]。目前可以回溯的相对较早的高功率级联泵浦光纤激光的报道是 IPG Photonics 公司在 2008 年 Laser Optics 会议上报道的 6 kW 级功率，这将此前的输出功率(3.5 kW)迅速提升至 6 kW[23]，随后在 2009 年、2010 年相继实现了 9.6 kW 和 10.5 kW 输出[9-10]。当然，限制光纤激光实现单模高功率输出的因素不仅仅是泵浦亮度，非线性效应(如受激拉曼散射、受激布里渊散射)[24-25]、模式不稳定效应[26-27]、光子暗化[28-29]、光纤熔丝[30-32]等均是限制单纤单模高功率输出及其稳定运行的重要技术瓶颈。

图 2 是文献[33]给出的万瓦级单模光纤激光结构示意图。可以看出，该万瓦级光纤激光由两级(一级为千瓦级种子源，一级为万瓦级放大器)组成。种子源对泵浦的亮度要求相对较低，当时可以采用半导体激光进行泵浦；而放大级则采用了 47 束 1018 nm 单模光纤激光(SM fiber laser pumps)作为泵浦源，每一束激光的输出功率为 270 W。所有泵浦源经过 1 个 57×1 的泵浦合束器(57/1 Pump combiner)后进入光纤内包层，可以推测泵浦合束器还有 10 个端口处于闲置状态，放大器实际泵浦功率约为 12.7 kW，最多可以注入的泵浦光达 15.4 kW。此外，文献[9]指出激光器的输出波长是 1070 nm，因此可以推定其是基于掺镱光纤实现的。从文献[34]引用的数据判断，激光器输出光谱的线宽是 5～6 nm。由于激光器结构中没有专门调制元件，因此可以确认激光器是连续波运行。

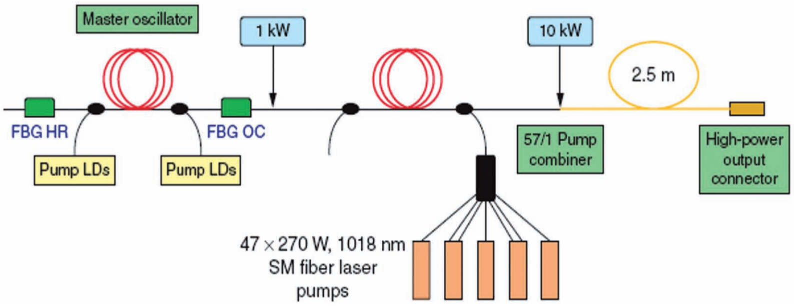

图 2　万瓦级单模光纤激光的结构示意图[33]

Fig. 2　Structural diagram of 10 kW-level single-mode fiber laser[33]

从上述的数据分析，简要概括万瓦单模光纤激光的若干特征：1)采用光纤激光泵浦掺杂光纤的级联泵浦技术；2)采用放大器结构；3)放大级的增益介质是掺镱光纤，输出波长是 1070 nm(有利于掺镱光纤实现高功率输出的波长[35-36])；4)激光输出线宽值比较“适中”，适合于对时间相干性没有特殊要求(如激光加工等)的场合；5)连续波运行。基于此，本文接下来主要从泵浦方式、系统结构、增益介质、激光线宽和时序特性等角度出发，详细梳理近十年高平均功率光纤激光的研究进展。

3　泵浦方式：从单一走向多元

泵浦源通常是光纤激光系统中最关键、成本最高的组件之一。随着半导体激光技术和双包层光纤激光工艺的发展，“半导体激光＋掺镱双包层光纤”一度是高功率光纤激光系统的标准配置，而半导体

激光作为一个重要组件，除了提供“泵浦能量”之外几乎没有其他功能。在一段时期内，半导体激光亮度的提升速度一度无法满足高功率光纤激光的发展需求，因此研究人员引入了级联泵浦等新的方案。近年来，随着半导体激光亮度的飞速提升以及新的科学问题的发现，光纤激光的泵浦方式逐渐由原先“半导体激光泵浦”的单一方式走向多元，并推动了光纤激光技术的发展。

3.1　半导体激光泵浦的高功率光纤激光

虽然半导体激光的亮度一度是限制光纤激光功率提升的“瓶颈”，然而，半导体激光技术并非停滞不前，而是一直在发展，近几年更是呈现出了高速发展的态势。图 3(a)和图 3(b)分别是 nlight 公司和 IPG Photonics 公司主页提供的亮度提升和成本降低的数据。可以看出，近十年来，半导体激光的亮度增加了一个量级以上，而成本降低了七成多，这为基于半导体激光泵浦的高功率光纤激光研制提供了良好的条件。

近年来，基于半导体激光泵浦的光纤激光输出功率持续提升。2015 年，国防科技大学课题组报道了基于半导体激光泵浦的全光纤单模光纤激光 3.15 kW 功率输出[37]。2017 年，德国耶拿大学课题组报道了基于空间结构的 4.3 kW 单模光纤激光[38]；同年，天津大学课题组报道了全光纤结构 5 kW 高光束质量输出[39]。2018 年，中国工程物理研究院基于自研光纤实现了半导体泵浦光纤激光 7 kW 级功率输出[40]，随后实现了超过 8 kW 级的功率输出[41]。自 2019 年以来，先后有多家单位实现了基于半导体激光泵浦的全光纤结构光纤激光 10 kW 功率输出[42-44]。虽然已有多家单位基于半导体激光泵浦实现了单纤万瓦级功率输出，但从文献报道的结果来看，输出光束质量离单模还有一定差距。

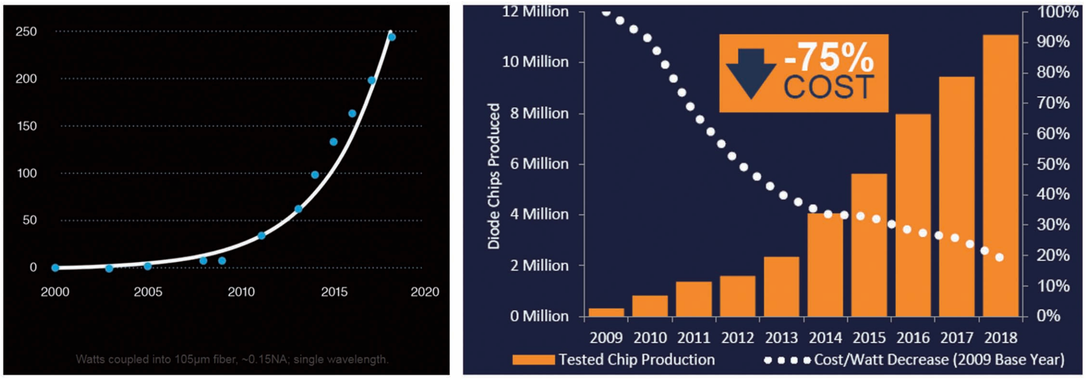

图 3　近年来半导体激光发展数据(引自 nlight 公司和 IPG Photonics 公司主页)。(a)亮度提升数据；(b)成本下降数据

Fig. 3　Development data of diode laser in recent years from homepages of nlight Inc. and IPG Inc. (a) Brightness increment data; (b) cost decrement data

3.2　级联泵浦技术的广泛使用

尽管半导体激光泵浦的光纤激光已经实现了单纤万瓦级功率输出，但这并不意味着级联泵浦技术已经不再应用；相反，级联泵浦技术被应用到更多类型的光纤激光器中。一方面，级联泵浦技术除了能大幅提升泵浦源的亮度外，在热管理方面也有优势[45]，再加上激发增益场的差别，在相同光纤参数下采用级联泵浦技术更有助于保持光束质量[46-48]；另一方面，近年来，半导体激光技术得到迅速发展，主要是用于泵浦掺镱光纤的 900～1000 nm 波段半导体激光，而用于泵浦掺铥、掺钬等其他类型增益光纤的 790～800 nm 波段和 1100～1200 nm 波段的半导体激光的亮度提升相对较慢，因此对高亮度的泵浦源仍有较大需求[49]。对于掺镱光纤，英国南安普顿大学课题组，德国耶拿大学课题组，新加坡南洋理工大学课题组、DSO 国家实验室课题组，中国科学院上海光学精密机械研究所、中国工程物理研究院、清华大学、上海交通大学、华中科技大学和国防科技大学课题组等均开展了基于级联泵浦的高功率单纤激光技术研究[50-68]，国防科技大学课题组报道实现了基于级联泵浦的单纤 10 kW 级高光束质量输出[62-63]和 4 kW 级窄线宽光纤激光输出(系统结构如图 4 所示)[52,64]；清华大学课题组报道实现了基于国产光纤的级联泵浦光纤激光 3 kW 级功率输出[54]、可调谐千瓦级输出[60]和基于商用光纤的 5.4 kW 输出[66]。

对于其他类型的增益介质，国内外也有多家单位开展了级联泵浦技术研究，比较有代表性的结果有：加拿大 Laval 大学等单位采用 1535 nm 光纤激光泵浦铒镱共掺光纤，获得了 264 W 的 1585 nm 激

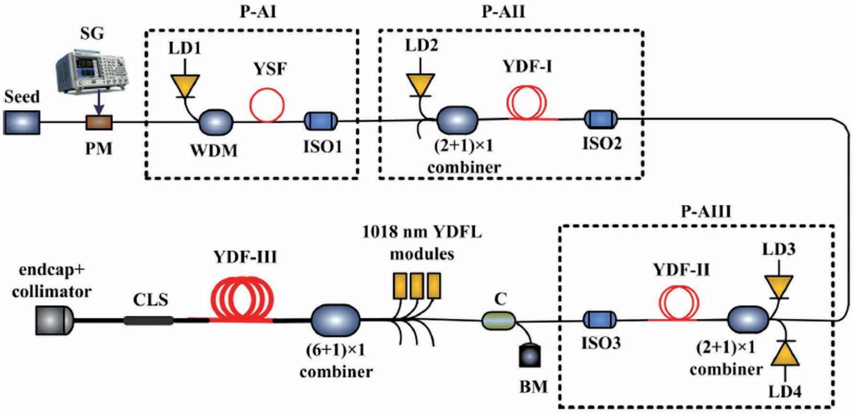

图 4　基于级联泵浦方式的 4 kW 窄线宽光纤激光系统结构[64]

Fig. 4　Structural diagram of 4 kW narrow linewidth fiber laser based on tandem pumping scheme[64]

光输出[69]；美国 BAE system 公司采用 1908 nm 光纤激光泵浦掺铥光纤，获得了大于 90% 的斜率效率[70]；新加坡制造技术研究所等单位采用 1940 nm 光纤激光泵浦掺铥光纤，获得了 40 W 平均功率的皮秒脉冲激光输出，斜率效率高达 87%[71]；澳大利亚 DSTO（Defence Science and Technology Organisation）课题组采用多束掺钬光纤激光泵浦掺钬光纤，获得了 400 W 高功率激光输出[72]。

本文讨论的级联泵浦（对应英文名称为 Tandem Pumping）和目前很多文献报道的“同带泵浦（对应英文名称为 In-band Pumping）”有明显的区别：前者主要从结构上阐述（即“级联”而非“直接”），后者主要从吸收发射谱的重合上阐述（即泵浦波长处于发射谱段，也属于吸收谱段）。如采用 1500～1600 nm 半导体激光泵浦掺铒光纤就属于“同带泵浦”；采用 900～1000 nm 半导体激光泵浦掺杂光纤产生 1100～1200 nm 光纤激光，再用 1100～1200 nm 光纤激光泵浦掺铥光纤就属于“级联泵浦”；采用 900～1000 nm 半导体激光泵浦掺杂光纤产生 1500～1600 nm 光纤激光，再用 1500～1600 nm 光纤激光泵浦掺铒光纤既属于“级联泵浦”，也属于“同带泵浦”。

3.3　基于新型泵浦技术的高功率光纤激光

随着高功率光纤激光研究的不断深入，泵浦源的功能不再仅仅是“提供能量”。研究人员发现，对泵浦源及其输出特性的调控，可以提升激光器的输出性能。德国耶拿大学等单位的研究表明，泵浦的强度噪声是影响模式不稳定效应产生阈值的重要因素，通过调控泵浦源的强度噪声，可以显著提高模式不稳定效应的产生阈值[73-75]；此外，泵浦源的强度噪声的传递方式还会对高功率激光的非线性效应产生影响[76-77]。清华大学课题组使用“半导体激光＋光纤激光”的双波长（976 nm＋1018 nm）泵浦方法，获得了 3.7 kW 的高功率激光输出[78]；英国南安普顿大学课题组使用多波长（950 nm＋976 nm）半导体激光泵浦的方法，获得了 1020 nm 单波长激光输出，效率达 51%[79]；本课题组采用超荧光光源泵浦的方法，有效改善了拉曼增益特性、提高了平坦度，在 40 nm 泵浦宽度的条件下，获得了 1116～1125 nm 区间的 19 波长激光输出，信噪比高于 30 dB[80]。

4　系统结构：从放大器结构到谐振腔结构、无腔结构

1999 年实现了百瓦级掺镱光纤激光，这是高功率光纤激光发展史上的重要事件[81]，它标志着光纤激光高功率输出从预测变成了现实。在此后的 5 年时间内，光纤激光的输出功率迅速从百瓦级提升至千瓦级[6-7,82-85]，在此过程中，激光器的系统结构是以谐振腔为主的。此后，由于单元器件承受功率、泵浦亮度等原因，更高功率的输出以放大器结构为主[86-92]。近年来，随着无源器件制备工艺和半导体激光亮度的提升，谐振腔结构的光纤激光输出功率迅速提高；另外，无腔结构的光纤激光等新概念也被提出并迅速实现。高功率光纤激光系统结构进入了一个多种类型并行发展的阶段。

4.1　谐振腔结构的高功率光纤激光器

与放大器结构相比，谐振腔结构具有结构简单、稳定性好等特点。光纤光栅是构建光纤激光谐振腔的重要元件。在早期研究过程中，由于光纤光栅的功率承受能力、泵浦亮度等因素，谐振腔结构的高功率光纤激光输出功率一般在数百瓦至千瓦级，通过功率放大的方式，可实现数千瓦甚至万瓦级功率输

出。近年来，随着光纤光栅制备工艺的改进、半导体泵浦源亮度的提升，光纤激光谐振腔的输出功率也得到了飞速提升。目前，日本藤仓公司是这一领域的领军单位，该单位自 2016 年以来在相关领域持续保持领先水平，先后报道了全光纤结构光纤激光谐振腔 3，5，8 kW 高功率高光束质量输出[8 kW 功率输出时光束质量约为 0.5 mm•mrad，对应的光束质量因子(M^2)约为 1.6]，其被应用于激光加工等场合[93-97]；德国耶拿大学基于自研光纤光栅也于 2019 年实现了光纤激光谐振腔结构 5 kW 功率输出，M^2 约为 1.3[98]；伊朗国家激光科学技术中心也于 2017 年实现了光纤激光谐振腔结构 3 kW 功率输出[99]，并基于该系统研究了泵浦结构对模式不稳定效应阈值的影响。

在国内，谐振腔结构光纤激光器的技术进步非常明显。国防科技大学课题组与中国科学院上海光学精密机械研究所等单位合作，在三年时间内先后突破了谐振腔结构 4，5，6，7 kW 功率输出[100-102]。目前，国内研究成果与国际领先水平的差距主要是在光束质量等方面。以 5 kW 光纤激光谐振腔为例，M^2 分别为 1.3[98] 和 1.7[101]。此外，在对实际应用效能影响十分明显的传能光纤长度方面，国内研究成果与国际领先水平也有明显的差距。谐振腔结构激光器的优势在激光加工等领域有大量应用需求，因此谐振腔结构的数千瓦级全光纤激光器产品近年来得到了广泛关注[103-104]。

4.2　无腔结构的高功率光纤激光器

2010 年前后，英国 Aston 大学课题组提出了一种基于“随机分布式反馈＋拉曼放大”机理的激光产生方法，不需使用谐振腔结构(或者半腔结构)即可产生激光输出[105]。该方法具有结构灵活、波长灵活、产生激光时序稳定等优点[106-107]，近年来输出功率得到了飞速提升[108-111]，输出功率已经从 2013 年的 10 W 量级提升至 2019 年的千瓦级[112-117]，通过功率放大的方式实现了 5 kW 功率输出(如图 5 所示)、窄线宽千瓦级功率输出[118-121]，并在非线性频率变换[122-123]、激光泵浦[124-125]等领域得到了广泛应用。

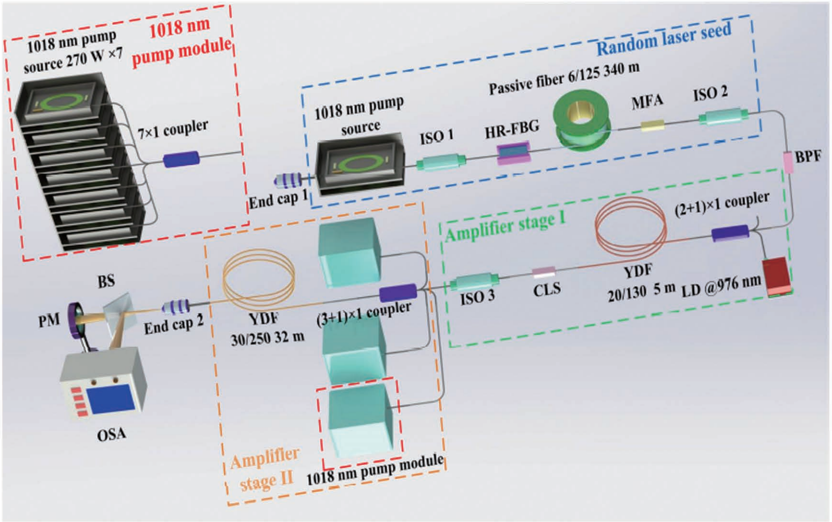

图 5　采用功率放大方式实现 5 kW 功率输出的系统结构示意图[121]

Fig. 5　Structural diagram of 5 kW output power system enabled by power amplification scheme [121]

5　激光波长：从短波到长波、从可见光到中红外

前文第 2 到第 4 节讨论的高功率光纤激光大都是基于掺镱光纤实现的，中心波长为 1.06～1.08 μm。实际上，掺镱光纤的辐射谱覆盖了 0.96～1.2 μm 波段[126]，虽然其余波段的净增益相对较小、难以实现高功率输出，但由于应用需求的牵引，这些波段上的激光也取得了重要进展[35-36,127]。此外，基于其他增益介质(包括掺杂光纤和无源光纤)也实现了高功率输出，使得高功率光纤激光的波长实现了“从短波到长波、从可见光到中红外”的大范围覆盖。

5.1　特殊波长掺镱光纤激光

文献[35]将掺镱光纤的输出波段分为短波波段(S)、常规波段(C)和长波波段(L)，其中常规波段对应的掺镱光纤净增益相对较大，比较容易实现高功率输出，而短波和长波波段(本节将处于这两个波段

的激光波长统称为特殊波长)输出高功率技术难度较大。尽管常规高功率光纤激光主要应用的工业加工等领域对激光的波长并不敏感,但对于高功率泵浦、非线性频率变换等领域,需要常规高功率光纤激光工作在特殊波长。第 2 节提到的 1018 nm 光纤激光就属于典型的特殊波长光纤激光,2010 年前后实现了单纤 300 W 级功率输出。此后,德国耶拿大学[128]、以色列 Soreq Nuclear 研究中心[129]、伊朗 Shahid Beheshti 大学[130]、土耳其 TUBITAK BILGEM 和 Bilkent 大学[131-132]、中国科学院上海光学精密机械研究所[133]、清华大学[134-136]、天津大学[137]和国防科技大学[138-140]等单位都实现了(数)百瓦级高功率输出;2020 年,美国 IPG Photonics 公司报道了 1.3 kW 1018 nm 光纤激光,M^2 小于 1.1[141]。

此外,更短波长(如 980 nm、1010 nm 等)输出也有相关报道,美国 IPG Photonics 公司实现了 750 W 1007 nm 光纤激光输出[141],美国 Clemson 大学、德国耶拿大学、国防科技大学等单位都实现了(数)百瓦高功率 980 nm 光纤激光[142-150]。研究表明,采用更短波长泵浦有利于提高泵浦吸收效率[151]。对于长波波段[152-157],国防科技大学课题组基于常规双包层光纤实现了百瓦级 1150 nm 掺镱光纤激光[154]和 30 W 级 1178 nm 光纤激光[153],日本电气通信大学等单位利用光子带隙光子晶体光纤实现了 167 W 1178 nm 激光输出[156]。

5.2 掺铒与掺铥/钬光纤激光

当前,光纤激光的功率纪录几乎都是基于掺镱光纤实现的,激光的中心波长大都在 1 μm 波段。近年来,基于掺铒光纤/铒镱共掺光纤和掺铥/掺钬光纤的 1.5 μm 波段光纤激光和 2 μm 波段光纤激光也取得了重要突破。在 1.5 μm 波段,尽管早在 2005 年就实现了全光纤结构百瓦级功率输出,但此后发展较为缓慢。近年来,美国 Clemson 大学、Coherent 公司,俄罗斯科学院,法国 Bordeaux 大学,加拿大 Laval 大学、CorActive 公司和英国南安普顿大学等单位开展了深入研究,逐渐形成了级联泵浦掺铒光纤和半导体泵浦铒镱共掺光纤两条技术路线[68,158-169],分别实现了 300 W 级(单模)[164]和 600 W 级(多模)[163]功率输出。

在 2 μm 波段,主要采用的增益介质是掺铥光纤和掺钬光纤[168-171],目前的最高功率千瓦级和 400 W 级,分别于 2010 年[18]和 2013 年实现[72]。近年来没有更高的功率报道,推测主要原因是受限于泵浦源亮度以及高功率运行时严重的热效应等因素,比如 2018 年前后德国耶拿大学基于空间结构实现了飞秒掺铥光纤激光千瓦级功率输出[172-174],系统中采用的泵浦源亮度与 2010 年的文献报道差别不大,而且主放大级效率在 60%左右,产生的废热为 500 W 级,与 5 kW 级掺镱光纤激光中产生的废热相当,进一步提升功率可能会面临模式不稳定等问题[175-176]。采用级联泵浦技术是降低废热、提升 2 μm 波段激光输出功率的技术手段[49,177]。

另外,掺铒光纤激光和掺铥光纤激光的波段也有“短波波段、常规波段和长波波段”的提法[178-180],其实掺镱光纤激光输出波段的划分在很大程度上是借鉴了掺铒光纤激光。级联泵浦的掺镱光纤激光、掺铒光纤激光和掺铥光纤激光通常都是利用“短波波段”泵浦“常规波段”或者“长波波段”来实现的。

图 6 所示是上述三类掺杂光纤的增益谱覆盖范围,其中曲线为石英光纤中不同波长激光的传输损耗。对于图 6 中未覆盖的“空白区域”,科研人员还采用拉曼增益或其他类型的掺杂光纤(如掺铋光纤)实现对应波段的激光输出。

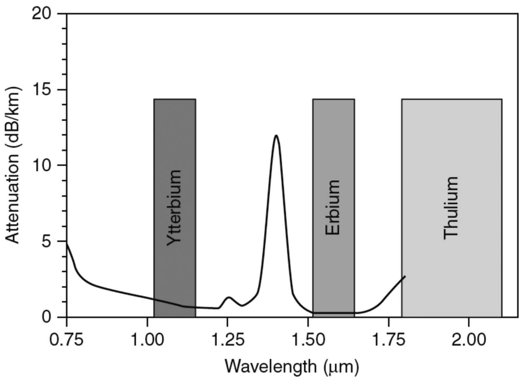

图 6 常见的三类掺杂光纤的增益谱覆盖范围[33]

Fig. 6 Covering ranges of gain-spectra of three typical doped fibers[33]

5.3 高功率拉曼光纤激光

鉴于掺杂光纤在部分波段净增益小、难以实现高功率输出的难题,科研人员通过引入拉曼增益来实现特殊波长的高功率激光输出[181-182]。随着激光物理研究的不断深入,基于无源光纤的拉曼激光以及基于“有源光纤+无源光纤”的混合增益机制也成为实现高功率激光输出的重要技术途径[183]。具体实施时,可以采用单级结构和放大器结构。

在单级结构方面,具体包括谐振腔结构、复合谐振腔结构和无腔结构等方式,其中无腔结构已在第 4.2 节简要介绍,科研人员已经实现了千瓦级功率

输出。基于谐振腔结构，在纤芯泵浦的方式下，已经实现了百瓦级功率输出[184-185]；在包层泵浦的方式下，已经实现了千瓦级功率输出[186-191]。基于复合谐振腔结构[192-193]，已经实现了 2 kW 级功率输出[193]，中心波长为 1120 nm，同比之下基于掺杂光纤的 1120 nm 波段全光纤激光器的最高功率为 300 W 量级[194]，充分体现了复合腔的技术优势。

在放大器结构方面，基于纤芯泵浦和包层泵浦无源光纤，均已实现了千瓦级功率输出[195-198]；基于“有源光纤＋无源光纤”的混合增益机制，已经实现了数千瓦功率输出[199-203]，并且在特殊波长窄线宽高功率激光输出方面展现了突出优势[203]。图 7 总结了近年来高功率拉曼激光输出功率（基于无源光纤）的提升过程，可以看出，高功率拉曼光纤激光正在进入一个高速发展的阶段。当然，进一步提升拉曼激光的输出功率，也会面临模式不稳定以及多重限制效应等带来的技术挑战[204-207]。

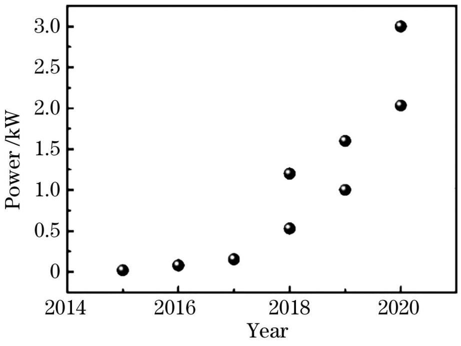

图 7　高功率拉曼激光输出功率的提升过程

Fig. 7　Output power scaling of high power Raman laser

5.4　可见光与中红外光纤激光

掺镱、掺铒（铒镱共掺）、掺铥/掺钬光纤是研究较多的高功率光纤激光类型，它们对应的输出波段分别为 1，1.5，2 μm 波段，第 5.3 节介绍的拉曼光纤激光技术几乎实现了近红外波段的全覆盖。除此之外，3～5 μm 中红外波段以及可见光波段光纤激光也有广泛的应用需求[208-211]，本节对这两个波段的研究进展进行介绍。

2010 年前后，日本 Kyoto 大学、美国 New Mexico 大学等单位先后实现了 2.8 μm 波段附近中红外激光 10 W 级功率输出，这标志着中红外光纤激光迈入了高功率阶段[212-215]。近年来，加拿大 Laval 大学、澳大利亚悉尼大学、日本 Osaka 大学、国内深圳大学、吉林大学等单位在高功率中红外光纤激光技术领域取得了重要进展[216-221]，加拿大 Laval 大学的 2.8 μm 波段中红外激光的输出功率突破了 40 W[219]，如图 8 所示，并且有超过 100 h（输出功率大于 20 W）的长时间稳定工作报道[220]。

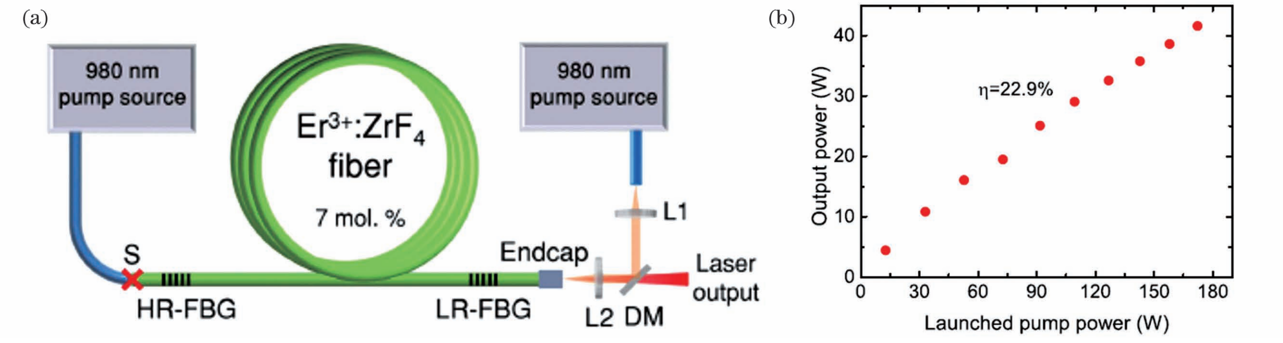

图 8　输出功率大于 40 W 的中红外光纤激光系统[219]。(a)结构；(b)实验结果

Fig. 8　Mid-infrared fiber laser with ＞ 40 W output power[219]. (a) Structural diagram; (b) experimental result

在可见光波段，由于增益介质制备和泵浦源亮度等原因，通常采用近红外变频等方式获得高功率输出[222]。近年来，由于相关工艺和技术的进步，日本千叶工业大学、加拿大拉瓦尔大学、国内厦门大学等单位在使用半导体激光直接泵浦掺杂光纤实现高功率可见光输出方面取得了一系列重要进展，目前已经实现(数)瓦级功率输出[223-227]。

6　激光线宽：从超窄线宽到超连续谱

依照目前专业技术文献对线宽的通用描述方式，高功率光纤激光大致可以分为五个类型。一是单频激光（单纵模激光），指输出仅含有一个频率（纵模）的激光，线宽通常在 100 MHz 以内，也有很多 10 kHz 以内的文献报道[228-232]。二是窄线宽激光。目前对于窄线宽的“窄”没有统一的定义或标准，文献[233]提出窄线宽激光一般指线宽小于 0.1 nm 的激光，但后续也有将线宽窄于 0.3 nm 的激光称作窄线宽激光的报道[234-237]。考虑到目前窄线宽激光的主要应用领域是部分光束合成（具体包括相干合成和光谱合成）和非线性频率变换等对激光相干

性有一定要求的场合，而常规高功率光纤激光的线宽一般在数 nm 量级，本文将窄线宽激光的线宽定义为＜1 nm 量级，即线宽范围处于单频激光和常规激光之间。三是常规激光，一般指基于经典谐振腔结构实现的高功率激光，或者经典谐振腔作为种子经过功率放大实现的高功率激光，线宽典型值是数个 nm。常规激光主要应用于工业领域（能量沉积型应用，如切割、焊接等），对相干性没有特殊要求，本文第 2 到第 4 节介绍的激光器大都属于此类。四是宽谱激光，通常采用超荧光等方法产生，线宽宽于常规激光，窄于超连续谱，主要用于光纤陀螺、激光泵浦等领域[238-239]。五是超宽谱激光，主要指高功率超连续谱，它的线宽值已经宽于常规掺杂离子的增益谱（即便是宽带增益，由于增益竞争等原因，很难直接实现数十 nm 输出），需要通过光纤中的非线性效应实现[240-242]。上述五种类型的高功率光纤激光的基本情况如表 1 所示。需要说明的是，表 1 中标注的线宽分类标准并非绝对值，而是面向主要应用领域提出的参考标准。

表 1　从光谱角度划分的不同类型的光纤激光及其主要应用领域

Table 1　Types of fiber lasers according to spectra and main application fields

Type	Linewidth	Main application field
Single frequency laser	＜100 MHz（corresponding to ～0.3 pm@1 μm）	Coherent detection，sensing，etc.
Narrow linewidth laser	＜1 nm	Beam combination，nonlinear frequency conversion，etc.
Common laser	1–10 nm	Laser processing，etc.
Broadband laser	10–50 nm	Fiber gyro，laser pumping，etc.
Super-broadband laser	＞50 nm	Spectral analyzation，imaging，etc.

由于线宽不同，相同输出功率下激光的谱功率密度不同，产生的非线性效应的强度和类型也不同。因此，上述五种类型的光纤激光在输出功率提升的过程中，面临的技术瓶颈和制约因素也有较大差别[243-247]：对于单频激光和窄线宽激光，受激布里渊散射（SBS）效应是限制功率提升的重要因素[248-249]，而在其他三种类型的激光器中一般不会发生；常规激光功率提升的主要受限因素之一是受激拉曼散射（SRS）效应，而 SRS 效应却是高功率超宽谱激光产生的重要机制；新近发现的模式不稳定（TMI）效应是光纤激光功率提升的技术瓶颈[250-251]，已经表现出明显的线宽相关性[252-253]。图 9 为文献[254]报道的高功率全光纤结构单频激光的系统结构，系统中采用 1030 nm 激光作为种子抑制 TMI，采用锥度光纤同时起到抑制 SBS 和 TMI 的作用，最终实现了大于 500 W 的功率输出。

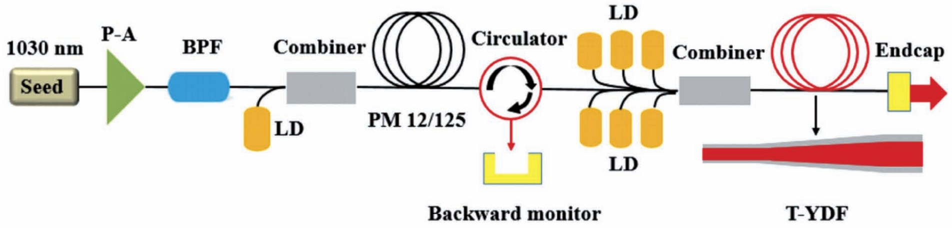

图 9　550 W 级全光纤结构单频激光的系统结构[254]

Fig. 9　Structural diagram of 550 W-level all-fiberized single-frequency laser[254]

此外，虽然时域和光谱通常被当作不同维度的激光特性加以考察，但由于测不准关系等引入的时频特性的耦合，时域和光谱特性往往是耦合的，不同脉宽的光纤激光器对应的线宽类型不一致。比如皮秒/飞秒激光等（超）短脉冲激光就不可能实现单频输出，飞秒激光就不可能实现窄线宽输出。

尽管泵浦技术、有源光纤和无源器件等共性技术的高速发展为高功率光纤激光的研制奠定了良好的基础，但由于上述因素的影响，不同类型的光纤激光器发展呈现出了不同的速度和特征。目前，全光纤结构的单束单频激光、窄线宽激光、常规激光、宽谱激光和超宽谱激光的最高输出功率分别为 500 W 级、4 kW 级、20 kW 级、3 kW 级和 400 W 级[252-259]，具有一定程度的“对称性”。尽管最高输出功率存在量级上的差别，但由于不同场景对激光功率的需求不同，五种不同类型的光纤激光器已经并将继续在

各自的应用领域大放异彩。

7　高平均功率脉冲光纤激光器

以上以连续波激光器为主要对象综述了不同类型的高功率光纤激光器，本节从时序的维度（从脉宽划分，主要可以分为准连续、纳秒、皮秒和飞秒等类型）简要介绍高功率脉冲光纤激光器的研究进展。

高功率准连续光纤激光和纳秒脉冲激光主要应用于工业领域和激光变频等科研领域。2015 年，德国耶拿大学报道了基于级联泵浦结构的高功率准连续光纤激光，采用商用盘片激光作为泵浦源（激光器运行在 10%的占空比状态）泵浦掺镱光纤，获得了峰值功率为 6.8 kW 的 1071 nm 光纤激光输出；而当系统工作在连续波状态时，则输出功率为 985 W[260]。同年，美国 IPG Photonics 公司报道了千瓦级准连续窄线宽光纤激光（平均功率为 1.03 kW，峰值功率为 4.9 kW，0.5 nm 线宽范围内的功率占比大于 94%），并利用该激光作为泵浦源进行了非线性频率变换，获得了 700 W 532 nm 绿光和 160 W 355 nm 紫外光输出[261]。通过访问 IPG Photonics 公司官网可以查询，目前高功率准连续光纤激光的平均/峰值功率已经达到 2 kW /20 kW[262]。

在纳秒激光方面，德国耶拿大学课题组采用 1 m 长的棒状光子晶体光纤作为放大器增益介质，实现了纳秒脉冲激光 2 kW 平均功率输出，M^2 约为 3[263]。通过访问 IPG Photonics 公司官网可以查询，目前高功率纳秒光纤激光的平均功率已经达到 2 kW（脉宽为 25～100 ns，重复频率在 2～50 kHz 范围内可调），最大脉冲能量可达 100 mJ[264]。

高功率皮秒光纤激光和飞秒光纤激光主要应用于工业加工领域。与准连续激光和纳秒激光不同，皮秒/飞秒脉冲短，峰值功率更高，更容易产生非线性效应。基于棒状光纤的空间结构高功率光纤激光在抑制非线性方面有优势，许多具有高技术指标的成果都是采用这种方案实现的[265-269]。同时，基于传统全光纤结构的超快激光在可柔性操作等方面有优势，近年来成为这个领域的研究热点。在皮秒激光方面，2009 年，国防科技大学课题组实现了全光纤结构皮秒激光百瓦级功率输出[270]。之后，该类型的输出功率取得了迅速发展[271-274]，目前最高输出功率已经达到 600 W 级，基于掺铥光纤的皮秒脉冲激光的输出功率也突破了 400 W 级[275-276]。在飞秒激光方面，2013 年，美国 PolarOnyx 公司实现了全光纤结构飞秒激光千瓦级功率输出[277]，堪称本领域里程碑事件。在国内，国防科技大学课题组 2016 年报道了全光纤结构飞秒激光 300 W 级功率输出[278]。

值得指出的是，脉冲激光的峰值功率高，相对连续激光而言，更容易引发非线性效应，功率定标放大的难度更大。目前，脉冲光纤激光的最高平均功率与连续激光相比，尚有量级上的差距。基于此，在连续波领域广泛应用的相干合成技术[279-281]近年来被广泛应用于脉冲光纤激光领域[282-285]，并取得了一系列重要进展。从 2013 年以来，德国 Jena 大学课题组在高平均功率超快激光相干合成和高脉冲能量超快激光相干合成等方面取得了重要突破[286-292]，分别实现了万瓦级高平均功率和 20 mJ 级大脉冲能量输出。图 10 是文献[292]报道的采用 16 束激光相干合成获得 10 mJ 大脉冲能量激光输出的实验系统和典型结果，平均功率达 1 kW、脉宽为 120 fs。

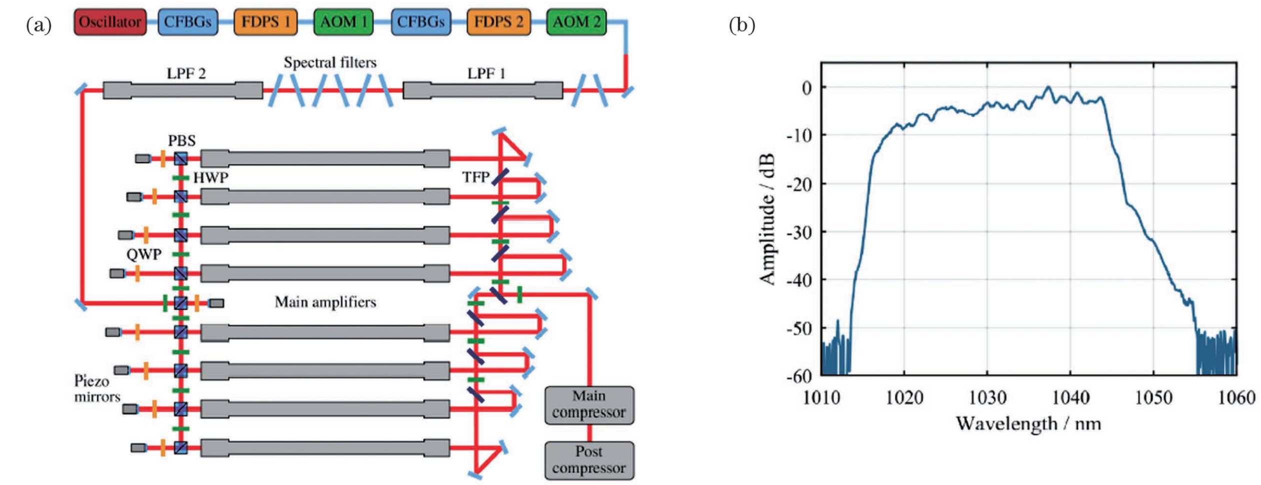

图 10　16 束激光相干合成系统[292]。(a)结构；(b)满功率输出时的光谱

Fig. 10　16-lasers coherent beam combining system[292]. (a) Structural diagram; (b) spectrum at maximal output power

此外，日本 Osaka 大学的科研人员通过 8 束亚纳秒脉冲激光合成实现了千瓦级 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 激光输出和平均功率为 300 W 的 347 nm 激光输出[293]。

8　技术发展趋势

前文第 3 至第 7 节结合万瓦级单模光纤激光的实现方案，从泵浦方式、系统结构、增益介质、激光线宽和时序特性等方面梳理了近年来高功率光纤激光领域的研究进展，但限于篇幅，难以进一步深入全面地介绍整个光纤激光领域的发展态势。此外，各个观察维度之间是相互关联的，可以形成很多新的视角，比如“中红外”+“超短脉冲”、“可见光”+“超连续谱”，等等。对此可以阅读此前出版的相关综述文献，如高功率光纤激光技术及其应用[2,4,15]、拉曼光纤激光[294]、线偏振光纤激光[295]、单频与窄线宽光纤激光[296]、中红外光纤激光[297]、激光超连续谱[298]以及光纤激光光束合成等[299-300]。如果说 IPG Photonics 公司提出的三个“任意”[301-302]（即任意功率、任意波长、任意脉宽）是从宏观和应用层面对光纤激光的发展进行了很好的展望，那么具体到技术层面，从近期发表的文献来看，高功率光纤激光技术呈现出向“可控”方向发展的趋势，具体表现如下。

一是激光脉冲特性可控。激光的脉冲特性包括重复频率、脉宽、波形等多个方面。通过“种子”+“放大”结构，科研人员很早就实现了对高功率光纤激光的重复频率和脉宽的控制。近年来，伴随着先进制造、生物医学等领域的发展，人们发现脉冲的形状对应用效果有重要影响。基于放大器中的增益饱和等物理效应，科研人员提出了“预调制”、“预补偿”等方式[303-307]，通过引入计算科学和光电混合系统，也实现了脉冲波形的几乎任意可控（如平顶波形、椭圆波形、“M”型）输出[308]。

二是激光光谱特性可控。激光的光谱特性包括中心波长、线宽、谱型等多个方面。通常光谱可控是指中心波长可调。对于高功率光纤激光而言，科研人员很早就实现了中心波长可调，但是可调谐范围往往局限在增益光纤发射谱能覆盖的波段，一般在百纳米级以内。近年来，随着非线性效应的引入，上述调谐范围已经被大大拓展，中国科学院上海光学精密机械研究所课题组通过激发不同阶数的受激拉曼散射效应，实现了近千纳米范围内的中心波长可调谐输出[309-310]，如图 11 所示。线宽可调谐的高功率光纤激光近年来也取得了一系列成果，国防科技大学课题组实现了百瓦级宽带激光输出并实现了应用[311-312]，印度科学院课题组实现了 20 W 级线偏振（消光比大于 20 dB）线宽连续可调窄线宽光纤激光，可调范围是～2.88 GHz 到 ～9.88 GHz[313]。随着谱型影响非线性效应等现象的发现和物理机制的深入研究[314]，科研人员对高功率光纤激光的光谱控制能力不断增强，这会进一步促进相关研究和应用。

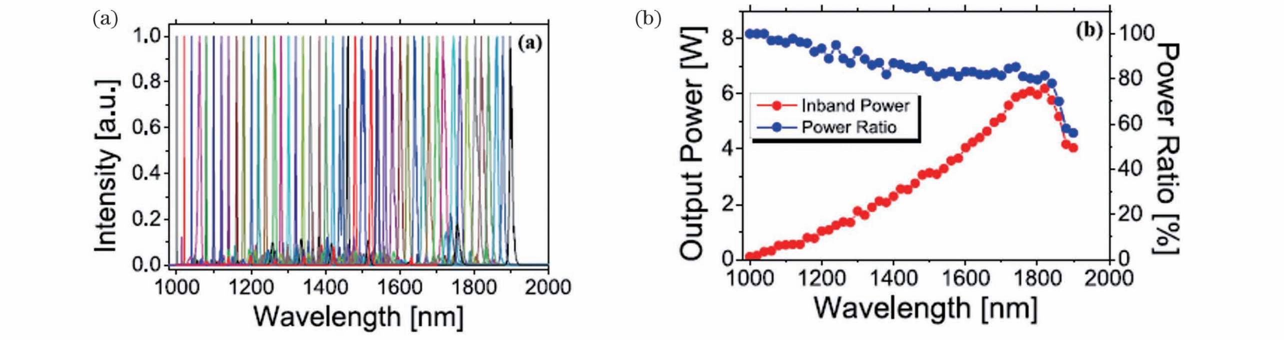

图 11　近千纳米范围可调光纤激光器[310]。(a)光谱；(b)输出功率特性

Fig. 11　Tunable fiber laser with nearly kilo-nanometer tuning range[310]. (a) Spectra; (b) output power characteristics

三是空间模式特性可控。长期以来，人们依照输出的空间模式特性，将高平均功率光纤激光主要分为单模光纤激光和多模光纤激光两类，并将其分别应用于不同的场景（如远距离能量输运和先进制造等）。一般而言，模式特性可控的激光输出功率较低，主要应用在通信等场合[315-319]。近年来，随着光纤器件技术的发展和制造类应用需求的增加，空间模式可控的光纤激光逐步实现了高功率输出。通过运用光栅选模法，可以实现百瓦级条件下低阶模式和高阶模式的可切换输出[320-321]；通过主动偏振控制的方法，可以实现千瓦级条件下低阶模式和高阶模式的可切换输出[322-323]；通过特殊的光纤和器件设计，可以实现千瓦

条件下光斑模式的可控输出[324]。图 12 所示为 nlight 公司的模式可调光纤激光器的输出特性[325]，模式可控的高功率光纤激光是当前先进制造领域的热点[326-327]，有可能会带来重要的技术革新。

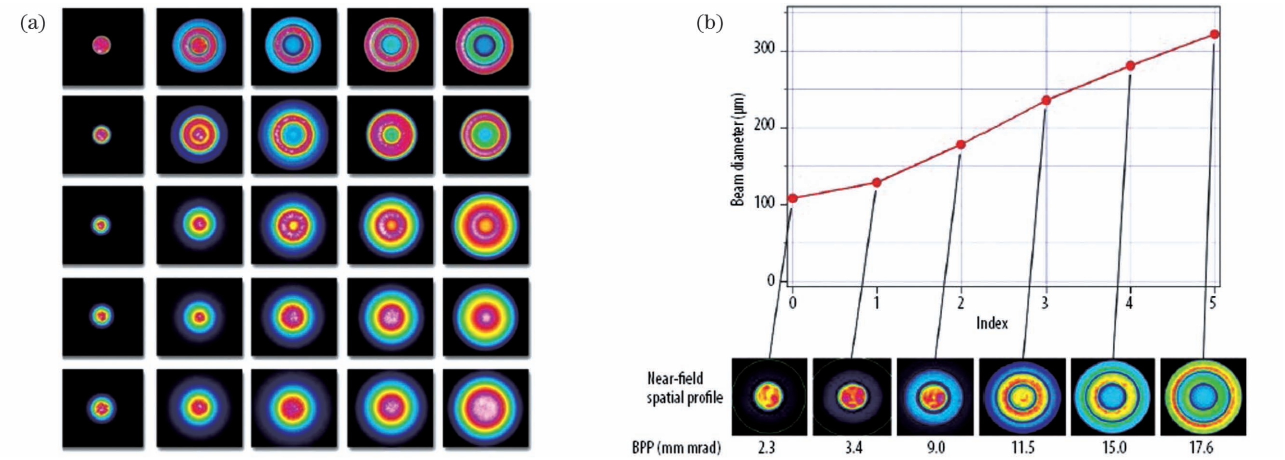

图 12　nlight 公司的模式可调光纤激光器的输出特性[323]。(a)输出光斑形态；(b)不同光斑的传输参数和光斑直径

Fig. 12　Output characteristics of mode-tunable fiber laser from nlight Inc.[323]. (a) Output spot patterns; (b) transmission parameters and diameters of different spots

9　结束语

光纤激光器是较早实现的激光器类型之一。第一台激光器发明后不久，1960 年 6 月，America Optical 公司的 Snitzer[328] 就提出了基于光纤的光学 Masers 谐振腔的概念；1961 年，Snitzer[329] 在掺钕玻璃波导中观察到了激光现象。如今六十年过去了，通过科研工作者的共同努力，光纤激光与半导体(泵浦)、先进材料(掺杂光纤、无源光纤)和精密制造(光纤熔接、无源器件制备)等领域交叉融通，得到了飞速发展，已经在通信传感、先进制造、生命医疗、能源勘探、科学前沿和国防军事等诸多领域得到了广泛应用。光纤激光是科技领域关注和支持的重点，以我国为例，国家科技部“十四五”重点研发计划项目[330]、国家自然科学基金项目[331] 等均涉及了光纤激光，相关学会举办了光纤激光领域的专门研讨会议[332]。可以预见，光纤激光的科学研究水平将持续提升，光纤激光也将继续改变人类的生产生活方式。

致谢　感谢李阳、郭琨、李思成、王广建、刘流、李巍、李浩博等同学在文献整理方面的协助，感谢叶俊在图片绘制方面的贡献。

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High Average Power Fiber Lasers: Research Progress and Future Prospect

Zhou Pu*, Leng Jinyong, Xiao Hu, Ma Pengfei, Xu Jiangming, Liu Wei, Yao Tianfu,
Zhang Hanwei, Huang Liangjin, Pan Zhiyong

College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha,
Hunan 410073, *China*

Abstract

Significance High-average-power fiber lasers have many important applications in advanced manufacturing, energy exploration, and national security benefit from the advantages of compact structure, high electro-optical efficiency, and flexible operation. In 2009 and 2010, IPG Photonics demonstrated a single-fiber single-mode laser with an output power of 9.6 kW and 10.5 kW, respectively, two important milestones in the field of fiber lasers. In the past 10 years (2010–2020), high-average-power fiber lasers and systems of various operation bands have developed rapidly and moved towards large-scale applications. In this paper, the research progress of high-average-power fiber laser technology in the past decade is reviewed.

Progress Firstly, the realization history and parameter analysis of 10 kW single-mode fiber laser are given, and the important characteristics of 10 kW single-mode fiber laser is summarized. Specifically, the first one is the tandem-pump technology, the second one is the amplifier structure, the third one is ytterbium ion as the gain medium of the amplifier stage, the fourth one is that the relatively moderate laser output linewidth, and the fifth one is continuous wave operation.

Second, the pump technology of high-average-power fiber lasers shifts from single to multiple. The pump source is one of the most critical and costly components in a high-average-power fiber laser system. With the development of semiconductor laser technology and double-clad fiber laser technology, semiconductor laser and ytterbium-doped double-clad fiber are once more the essential configurations in a high-average-power fiber laser system. For a period of time, the brightness of semiconductor lasers is unable to meet the development of high-average-power fiber lasers, so researchers begin to introduce new solutions such as tandem-pump technology. In recent years, with the rapid increase in the brightness of semiconductor lasers and the continuous discovery of new scientific issues, the pumping technology of high-average-power fiber lasers has gradually diversified, which has promoted the development of fiber laser technology.

Third, the system structure of high-average-power fiber lasers expands from the amplifier structure to the resonant cavity structure and cavity-free structure. In recent years, with the development of passive devices and semiconductor lasers, the output power of fiber lasers with resonant cavity structures has increased rapidly. In addition, new concepts such as fiber lasers without cavity structures have also been proposed and quickly realized. The high-average-power fiber laser system structure has entered a stage in which various system structures develop parallelly.

Fourth, the operation wavelength of high-average-power fiber lasers begins to expand from a short wavelength region to a long wavelength region, and from visible lasers to mid-infrared lasers. Although the radiation spectrum of ytterbium-doped fibers covers 0.96 μm to 1.2 μm, the net gain of the sidebands is relatively small and it is difficult to achieve a high-average-power output directly. Due to the traction of important applications, significant results have been achieved in the above fields. In addition, other new gain media including doped fibers and passive fibers have also been applied to realize a high-average-power output, which enables the operation wavelength of high-average-power fiber lasers to cover from shortwave to longwave, and from visible to mid-infrared.

Fifth, the laser linewidth of high-average-power fiber lasers could cover from ultra-narrow linewidth to supercontinuum regions, and high-average-power pulsed fiber lasers have also been realized. The limiting factors for high-average-power fiber lasers with different laser linewidths are different. As for the single-frequency fiber lasers and narrow-linewidth fiber lasers, the stimulated Brillouin scattering (SBS) effect is one of the main issues in the power scaling. As for the broadband fiber lasers, the stimulated Raman scattering (SRS) effect is one of the main issues in the power scaling. In addition, the newly discovered mode instability (MI) effect becomes a technical bottleneck in the power scaling of high-average-power fiber lasers, which has also shown an obvious correlation with laser linewidth. Due to the high peak power of pulsed lasers, the nonlinear effects are more critical in high-average-power pulsed fiber lasers. Therefore, there still exists a gap in magnitude between the highest average power of pulsed fiber lasers and the highest average power of continuous-wave fiber lasers.

Prospects In future work, the high-average-power fiber laser technology is moving toward the stage of controllable, which is specifically manifested in three areas. The first one is the controllable pulse characteristics, including repetition rate, pulse width, and waveform. Researchers have achieved an early control of repetition rate and pulse width of high-power fiber lasers. The second one is the controllable spectral characteristics, including center wavelength, linewidth, and spectral shape. With the continuous discovery of phenomena such as the influence of spectral characteristics on nonlinear effects, the ability of scientific researchers to control the spectral characteristics of high-average-power fiber lasers is continuously enhanced. The third one is the controllable spatial-mode characteristics. Mode-controllable high-average-power fiber lasers are currently a hotspot in the advanced manufacturing, which may bring important technological innovations.

Key words fiber optics; high power laser; pump; structure; wavelength; Raman; linewidth; pulse

OCIS codes 060.3510; 060.2310