科学通报 2017 年 第 62 卷 第 32 期：3719 ~ 3728

《中国科学》杂志社
SCIENCE CHINA PRESS

香山科学会议 专栏　进　展

第570次学术讨论会 • 高功率高光束质量半导体激光技术发展战略

高功率、高光束质量半导体激光器研究进展

张俊[1,2], 陈泳屹[1,2†], 秦莉[1,2†], 彭航宇[1,2*], 宁永强[1,2], 王立军[1,2]

1. 中国科学院长春光学精密机械与物理研究所, 长春 130033;
2. 发光学及应用国家重点实验室, 长春 130033

* 联系人, E-mail: penghy@ciomp.ac.cn

† 同等贡献

2017-03-26 收稿, 2017-06-05 修回, 2017-06-05 接受, 2017-09-07 网络版发表

国家自然科学基金(61574141, 61404137, 61535013, L1524007)、中国科学院学部学科发展战略研究项目(2015-XX-C-2)和中国科学院前沿科学重点研究项目(QYZDY-SSW-JSC006)资助

摘要　半导体激光器拥有效率高、体积小、重量轻、寿命长、波长丰富和可直接电驱动等诸多优点, 同时由于受到光束质量限制, 难以直接进行应用. 如何提升高功率半导体激光器的光束质量一直以来都是国内外研究热点. 本文主要面向工业加工及国防等领域对高功率、高光束质量半导体激光器的应用需求, 从半导体激光单元技术和合束技术两方面的研究进展进行了论述. 首先分析了激光单元结构与激光侧向、横向和纵向模式的关系, 总结了国际上控制模式特性的一些典型结构; 然后介绍了当前国际上高功率、高光束质量半导体激光合束技术及光源发展现状, 并分析讨论了各种激光合束技术特点及发展趋势; 最后展望了高功率、高光束质量半导体激光器的发展前景.

关键词　半导体激光器, 高功率, 高光束质量, 激光合束

与其他类型激光器相比, 半导体激光器效率高(达70%)、体积小(体积<0.1 cm^3)、重量轻(100 W激光芯片质量仅数克)、寿命长(数万小时)、波长丰富(可见至红外任意波长输出)及可直接电驱动. 早期对大功率半导体激光器的研究集中在如何提升功率, 如增加发光区条宽提高单元功率, 再二维集成提高整体功率, 但与此同时导致光束质量下降, 使其主要作为全固态激光器的泵浦源间接应用, 难以直接应用. 研究人员逐渐认识到半导体激光器的光束质量是与功率同等重要的参数, 提升高功率半导体激光器的光束质量是半导体激光器走向直接应用必须攻克的难关, 如何获得高功率、高光束质量半导体激光器成为国际半导体激光科学的研究前沿, 高功率、近衍射极限单元器件及合束光源成为半导体激光技术领域中的重大挑战. 为此, 美国和德国相继部署了ADHEL, BRIDLE及IMOTHEB等专项, 国内也在开展相关研究.

1　半导体激光单元技术的研究进展

目前, 实用化的高功率半导体激光单元器件主要基于边发射结构, 根据芯片外延和激光振荡特性, 光场模式分布在谐振腔的3个方向上, 即垂直于PN结的横模、平行于PN结的侧模和沿着光轴方向的纵模. 根据不同的使用条件, 采用不同方式控制各方向模式. 下面从这3个方面介绍半导体激光单元技术的研究进展.

1.1　侧向模式控制研究进展

高功率半导体激光单元器件的侧向模式是限制

引用格式: 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. 科学通报, 2017, 62: 3719–3728
Zhang J, Chen Y Y, Qin L, et al. Advances in high power high beam quality diode lasers (in Chinese). Chin Sci Bull, 2017, 62: 3719–3728, doi: 10.1360/N972017-00352

光束质量的主要因子. 高功率和高光束质量是相互矛盾的指标, 为了获得高功率, 侧向发光区尺寸通常越大越好(百微米量级), 但这又导致侧向光场模式限制变弱, 光束质量变差(数十倍衍射极限). 为了均衡功率和光束质量, 通常采用线亮度(B_{lat})评价, 定义为激光功率P与侧向光束质量Q_{lat}的比值, B_{lat}越大, 单元器件功率、光束质量综合指标越好.

通过刻蚀成窄脊结构, 减小侧向尺寸至微米量级, 可提升侧向光束质量. 瑞士Oclaro研制脊宽6 μm、腔长4.8 mm的980 nm激光单元, 实现连续2 W基模高斯光束输出, B_{lat}达6.4 W/(mm mrad), 最大光电转换效率63%[1]. 美国麻省理工采用板条耦合结构[2~5], 如图1所示, 脊宽4 μm、波导宽度5 μm、腔长10 mm的半导体激光器获得了连续输出3 W、B_{lat}比8.9 W/(mm mrad)的1060 nm单模激光输出, 最大光电转换效率45%[6]. 窄脊激光器提升B_{lat}具有很好的效果, 但由于腔面尺寸小, 高功率输出时腔面功率密度高, 容易造成腔面损伤, 需要特殊的腔面钝化处理.

为了降低腔面功率密度, 同时提高激光功率, 提出了种子振荡功率放大器(MOPA)结构, 它通过窄脊单模激光源产生种子光, 即振荡源(MO), 经过半导体放大器(PA)将振荡源激光放大[7~10], 当MO激光和PA放大器集成到一个芯片上时就形成锥形激光器, 同时还可以在芯片上集成光栅结构调制光谱线宽. 德国FBH(Ferdinand-Braun-Institut)研究所先后报道了多种波长的锥形激光器[11~14], 如图2所示, 808 nm波长M^2=1.3×3.9 W, B_{lat}为11.66 W/(mm mrad)[15]; 979 nm波长$M^2_{(1/e2)}$=1.1×11.4 W, B_{lat}为33 W/(mm mrad)[16]; 1030 nm波长$M^2_{(1/e2)}$=1.2×14.5 W, B_{lat}为36.8 W/(mm mrad)[17]; 1060 nm波长M^2=1.2×10 W, B_{lat}为24.7 W/(mm mrad)[18]. 在高功率输出条件下实现了高光束质量输出, 但由于工艺复杂、制作难度大, 目前仅应用在一些特殊场合, 未能大面积推广应用.

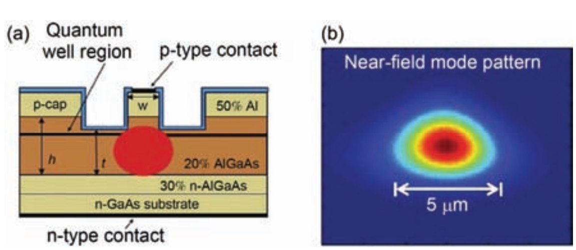

图 1 (网络版彩色)板条耦合半导体激光单元结构(a)和近场模式分布(b)

Figure 1 (Color online) Structure of the slab coupled diode laser emitter (a) and near-fieldmode pattern (b)

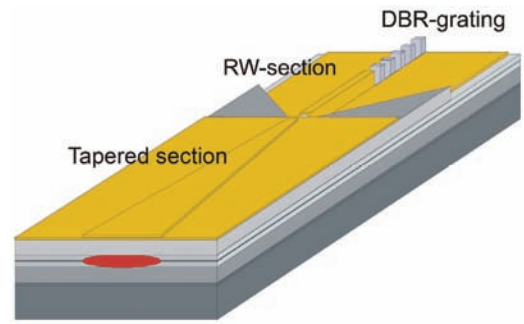

图 2 (网络版彩色)带有DBR光栅的锥形激光器示意图

Figure 2 (Color online) The typical tapered laser with DBR gratings

中国科学院半导体研究所、北京工业大学、中国科学院长春光学精密机械与物理研究所、长春理工大学均在MOPA结构的LD研究中取得了初步成果, 其中长春理工大学的MOPA结构LD输出功率可以达到6 W@线功率密度17 mW/μm, 所报道功率水平最高; 中国工程物理研究院应用电子学研究所通过多年研究高亮度LD输出功率可以达到4.3 W@9xx nm, 光束质量M^2<4; 在8xx nm波段国内只有中国科学院长春光学精密机械与物理研究所做了MOPA结构LD的相关研究, 实现输出功率1.4 W@线功率密度11 mW/μm, M^2~2.8.

德国FBH研究所也采用侧向反引导结构, 引入高阶模损耗机制, 压制高阶模起振, 改善光束质量, 条宽90 μm、腔长4 mm的969 nm激光单元, 实现连续7 W激光输出, B_{lat}达到3.5 W/(mm mrad)[19], 同时压缩侧向尺寸至20和30 μm[20], 采用腔长6 mm结构, B_{lat}分别达到6.5和5.5 W/(mm mrad). OSRAM在迷你bar上集成5个条宽50 μm的激光单元, 输出功率达到50 W, 光束质量优于11 mm mrad, B_{lat}达到4.8 W/(mm mrad)[21].

美国nLigh公司提出喇叭形结构(flared oscillator waveguide diodes)[22,23], 在谐振腔侧向制备锥形结构, 通过侧向最小位置限制横向模式, 出光腔面保持大尺寸, 降低腔面功率密度, 输出功率13 W, 光束质量3 mm mrad, B_{lat}为4.3 W/(mm mrad).

1.2 横向模式控制研究进展

2002年, 柏林工业大学的Ledentsov等人[24,25]在横向利用周期性生长的半导体材料层构成带隙光子晶体结构(LPBC), 限制横向模式, 在保持横向光束

质量近衍射极限条件下，增加横向波导尺寸，同时降低横向发散角．该结构的好处在于，横向波导尺寸的增加有效地降低腔面功率密度，使得激光单元腔面可承受更高功率，提升高功率工作下的可靠性，其次直接输出低发散角的激光束，采用球面透镜准直即可．但是较厚的有源区也限制了激光器效率．表1总结了LPBC半导体激光单元的发展现状[24,26~34]．柏林工业大学报道了系列研究结果，将横向发散角压缩至度量级．中国科学院长春光学精密机械与物理研究所采用双边布拉格反射波导结合低折射率光缺陷层结构，在808 nm波长获得了近圆形光束输出，90 μm条宽、1.5 mm腔长单管连续输出功率3.5 W, 4 mm腔长连续功率4.6 W，横向发散角降至4.91°.

1.3 纵向模式控制研究进展

对于高功率半导体激光器，常采用光栅控制纵向模式，这里主要在芯片结构上制备光栅：一是处于腔面的分布布拉格反射(DBR)结构；一是分布在谐振腔内的分布反馈结构(DFB).

（ⅰ）分布布拉格反射(DBR)激光器． DBR激光器以布拉格光栅作为激光器的一个谐振腔面．2010年，德国FBH研究所采用表面DBR结构获得了高功率激光输出，90 μm条宽单管输出功率14 W，最大转换效率为50%[35]．同年，他们采用六阶表面光栅结构，在激射波长974 nm，单模输出功率超过1 W, 3 dB光谱线宽仅为1.4 MHz[36]. 2011年，研制出1064 nmDBR激光器，连续输出功率180 mW、线宽为180 kHz[37]．中国科学院长春光学精密机械与物理研究所研制出38阶光栅耦合DBR半导体激光器，获得213 mW、线宽40 pm单纵模出光，边模抑制比40 dB[38].

（ⅱ）分布反馈(DFB)半导体激光器． 国外从2004年开始高功率DFB半导体激光器的研究，如德国FBH研究所研制出976 nm的一阶和二阶光栅器件，稳定基横模激射，输出功率分别为400 mW和2.4 W[39~41]，转换效率35.6%；美国Alfalight公司报道了975 nm二阶光栅器件，条宽100 μm、腔长2 mm的DFB激光器，连续输出功率3 W、电光转换效率50%、线宽0.3 nm[42]；韩国Gwangju科学院和加拿大国立研究院研制的1.55 μm三阶和二阶光栅DFB，单纵模功率为15 mW[43,44]；美国Eagleyard公司的976 nm的DFB激光器，单纵模输出功率150 mW(Eagleyard. EYP-DFB-0976-00150-1500-TOC03-0000[EB/OL]. www.eagleyard.com)．中国科学院长春光学精密机械与物理研究所研制出968.8 nm增益耦合DFB激光器，实现了144.6 mW、线宽40 pm单模出光，边模抑制比29 dB[45]；设计并研制出940 nm二阶光栅DFB半导体激光器，连续输出101 mW、光谱线宽90 pm、远场发散角为2.7°和7.3°、边模抑制比20 dB[46].

2 高光束质量半导体激光合束光源的研究进展

大功率半导体激光器根据单芯片集成的单元数量可分为激光单管(emitter)、激光线阵(bar)和激光叠阵(stack)．激光线阵为多个单管在水平方向的集成,

表 1 带隙光子晶体波导激光器发展现状

Table 1 Research status of photonic crystal waveguide diode laser

波段(nm)	年份	研制单位	发散角及相关性能指标
980	2002	柏林工业大学	横向6°[24]
	2003		横向5.5°~6°[26]
	2005		横向9.7°~10.7°，连续1.8 W，脉冲10 W[27]
	2008		横向4°~5°，侧向3.5°，连续1.3 W[28]
	2010		横向6°，侧向5°，连续2.2 W，光参量积0.47 mm mrad[29]
	2014	中国科学院半导体研究所	横向10.5°, 200 μm条宽连续输出功率5.75 W[30]
1060	2014	柏林工业大学	横向15°，侧向9°，峰值功率3 W[31]
	2015		横向15°，侧向11°, 6 μm条宽、2.64 mm腔长，连续1.8 W[32]
	2016		M^2=1.55, 9 μm条宽功率1.9 W[33]
808	2015	中国科学院长春光学精密机械与物理研究所	横向4.91°, 4 mm腔长连续4.6 W[34]

可连续输出几十瓦至数百瓦功率，主流结构为条宽为10 mm的标准bar(cm bar)或者条宽小于10 mm的迷你bar(mini bar)，通常采用传导热沉或者微通道去离子水冷却热沉封装．激光叠阵为多个微通道去离子水冷却热沉封装线阵在垂直方向的集成，可以连续输出百瓦至数千瓦的功率．提高半导体激光器功率可通过空间集成多个单管、线阵或叠阵，而如何获得高光束质量，需要进行激光合束．

当前实用化的高功率半导体激光合束光源主要基于非相干合束技术，发展经历了传统合束技术(TBC)到密集波长合束(DWDM)和光谱合束(WBC)并行发展两个阶段，如图3所示．1998~2007年，主要采用常规合束技术，由于激光单元性能的功率指标提升和常规合束技术的逐渐成熟，相同功率激光的光束质量提高近10倍．2007~2017年，随着芯片结构优化及元器件性能提升，常规合束光源(TBC)的光束质量提高近5倍，部分达到灯泵固体激光器(LPSSL)水平，密集波长合束(WBC)和光谱合束(SBC)为半导体激光技术领域注入新的活力，使得直接半导体激光源光束质量提高近15倍，超过LPSSL，达到CO_2激光器水平．这也使得高功率半导体激光器在“间接应用泵浦全固态激光器→直接应用熔覆、塑料焊接等功率密度低的场合→直接应用在金属焊接、切割等高端加工市场”的道路上快速稳健地前进．

2.1 常规合束(TBC)技术及进展

常规合束基于输出性能最佳的常规激光单元，合束过程中，不影响激光单元腔内谐振，仅通过外部光学元件对输出单元激光进行光束整形、空间合束、

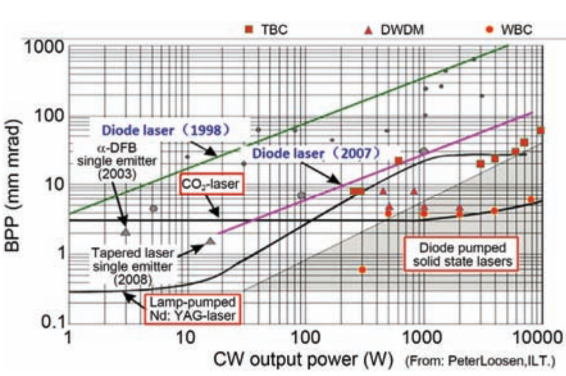

图 3 (网络版彩色)高功率半导体激光合束光源功率-光束质量研究进展

Figure 3 (Color online) Power vs beam quality research progress on high power diode laser combining sources

偏振合束和波长合束来提升整体功率、改善整体光束质量的过程．

根据激光单管、线阵和叠阵3种不同的封装形式，借助常规合束技术，目前已发展出激光单管合束光源、线阵合束光源和叠阵合束光源，实现了几十瓦至数万瓦级的直接输出或光纤耦合输出，应用在光纤激光泵浦、激光加工等．

单管合束光源是基于慢轴光束质量相对好的激光单管，快慢轴准直后，直接通过空间合束、偏振合束及波长合束实现耦合，可实现单波长几十瓦至六百瓦功率从100~200 μm芯径光纤输出，光束质量6~20 mm mrad，具有亮度高、成本低及可靠性好等优点，应用在光纤激光泵浦、激光医疗、激光照明等领域．美国nLight和日本Fujikura近期相继报道采用高功率、高光束质量的激光单管，将105 μm光纤耦合单波长模块功率从100 W提升至250 W[47~49]，用于光纤激光器泵浦，提升光纤激光器性能．意大利OPI公司通过波长合束进一步提高功率，105 μm/0.15光纤输出300 W功率[50]．北京凯普林通过空间叠加激光单管和偏振合束，200 μm/0.22光纤输出600 W[51]．

线阵合束光源多采用传导热沉封装、光束质量相对较好的迷你bar(5~10个激光单元)或者低填充因子的厘米bar(填充因子<20%)．主要原因在于常规的厘米bar(填充因子≥20%)，慢轴方向光束质量差，需要光束整形，光学结构复杂，加上散热限制单个激光线阵的输出功率一般在40~80 W，不能发挥厘米bar的功率优势．线阵合束光源功率一般在几百瓦至数千瓦，200~600 μm芯径光纤输出，光束质量20~60 mm mrad，主要应用在激光焊接等工业加工．代表性的厂商包括德国Dilas, Trumpf, Limo等[52~56]．德国Dilas公司采用OSRAM研制的新一代高性能迷你bar (B_{lat}~4.8 W/(mm mrad))，将其225 μm光纤输出标准产品功率从270 W提升至360 W[57]，并通过偏振合束和5个波长合束，400 μm/0.12光纤输出4600 W[58]．

叠阵合束光源借助微通道去离子水的高效散热，采用高填充因子厘米bar，单层激光叠阵功率可达数百瓦，经过数十层叠阵合束，能够实现数千瓦到万瓦功率，通过波长合束可将功率提升到更高水平．德国Laserline基于高亮度的激光叠阵，研发出系列高功率光纤耦合产品，连续输出功率从3 kW(400 μm/0.1)到20 kW(2000 μm/0.2)[59]，并报道了连续输出25~40 kW (2000 μm/0.2)的多波长合束光源[60,61]．目前叠阵

合束光源多用于激光熔覆, 表面硬化等对激光功率要求高、光束质量要求低的工业加工方面.

2.2 密集波长合束(DWDM)技术及进展

相对于传统波长合束相邻波长间隔不低于25 nm而言, 密集波长合束可将波长间隔缩小至纳米量级, 在不改变光束质量条件下, 数倍增加激光单元数量, 从而提高合束光源功率.

密集波长合束实现的关键在于: (1) 中心波长稳定的窄线宽激光单元, 可以通过直接在芯片刻蚀光栅或者通过外腔体布拉格光栅(VBG)反馈调制光谱; (2) 波长间隔小的合束元件, 如高波长陡度的二向分色元件、合束VBG等.

德国ILT研究所在迷你bar芯片上刻蚀不同周期光栅, 5个激光单元输出如图4所示的激光波长[62], 中心波长间隔2.5 nm, 采用4个二向分色镜将5个单元激光合束, 并聚焦进35 μm光纤[63]. 该方法实现的窄线宽单元结构稳定, 但是芯片光栅工艺要求非常高, 难度非常大, 在芯片制备时一旦某个单元光谱相对于位置出现偏差, 严重影响合束效率.

VBG外腔反馈是当前实现窄线宽激光输出的主要方式, 在常规激光芯片前腔面镀增透膜, 利用VBG衍射光作为种子光反馈回芯片腔内起振, 可实现谱宽窄至0.1 nm、温度漂移0.01 nm/℃的激光输出. 德国Dilas采用波长陡度为1 nm的二向分色镜, 对经过VBG线宽窄化处理的972, 976和980 nm 3束线偏振光波长合束并耦合进100 μm/0.2光纤, 出纤功率410 W[64]. 德国ILT通过VBG将6个商用激光模块波长锁定至935.9, 940.1, 944.0, 972.5, 976.5和979.7 nm, 然后采用二向分色镜进行密集波长合束和粗波长合束及聚焦耦合进光纤, 100 μm/0.17光纤输出超过800 W[65]; 德国Directphotonics也实现了波长间隔为4 nm的5束激光合束[66,67], 目前该公司已推出了功率500~2000 W、光束质量5 mm mrad、芯径100 μm的光纤耦合半导体激光源产品[68], 应用在金属切割.

德国RWTH以VBG作为合束元件, 通过精密温控4片相同VBG, 使其衍射波长和角度偏移, 分别调节至974.5, 976.0, 977.5和979.0 nm, 实现5束中心波长间隔仅为1.5 nm激光合束[69].

2.3 光谱合束(SBC)技术及进展

光谱合束技术利用单片色散元件, 可同时实现多束波长间隔低至0.1 nm的激光合束, 进一步提高合束单元数量.

目前发展较快, 并已形成产品的光谱合束原理如图5所示, 整个光源由前腔面镀增透膜的半导体激光芯片、变换透镜、光栅和外腔镜组成, 激光芯片输出多个单元光束经变换透镜作用, 成像到光栅同一点, 然后经光栅衍射, 由外腔镜将衍射光部分反射回光栅, 并沿原路返回, 回到原激光单元的光起振, 每个单元激光的起振波长严格满足光栅方程, 由于光栅入射角不同而衍射角相同, 使得各激光单元起振在各自不同的波长, 经过外腔镜输出的激光在近场和远场均重合, 因此实现功率为所有单元之和、光束质量与单个激光单元一致的激光输出. 美国麻省理

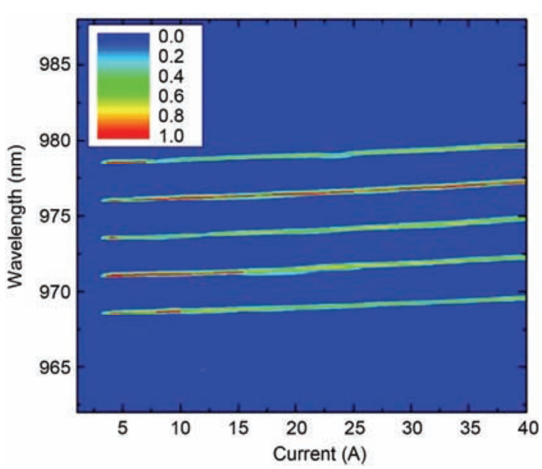

图 4 (网络版彩色)迷你bar输出波长间隔 2 nm的光谱分布

Figure 4 (Color online) Spectral distribution of five single emitters with the wavelength interval of 2 nm

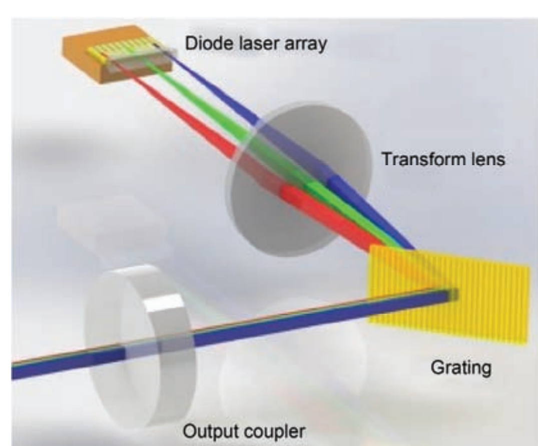

图 5 (网络版彩色)光谱合束原理

Figure 5 (Color online) Principe of WBC

工大学(MIT)对该技术的发展做了很多工作[70~72]，现产业化、成立Teradiode公司、推出了功率500 W/50 μm、2~8 kW/100 μm光纤输出产品[73]、应用在厚板金属切割、远程激光焊接等，是同等功率下激光加工光源的有力竞争者，并报道了360 W、2倍衍射极限[74]、亮度达10 GW/(cm^2 sr)的半导体激光源，直接将高功率半导体激光的亮度提高2个数量级，为高功率、高亮度半导体激光器发展指明新方向.

德国Trumpf公司提出了一种基于带宽达pm量级的窄带滤光片用于外腔反馈波长锁定结构[75]，如图6所示. 通过镀膜，使窄带滤光片具有角度-波长筛选特性，只有同时满足入射角和波长条件的光才能透过滤光片，这使得不同位置激光单元起振在不同波长，实现波长调制. 据文献报道，采用带宽50 pm (FWHM)的滤光片，将10个厘米bar波长锁定，整体输出谱宽为37 nm，每个厘米bar谱宽3.4 nm，每个激光单元80 pm(FWHM)，然后匹配合适的面光栅实现合束，并耦合进100 μm芯径光纤中，输出功率近500 W[76]，利用该技术，已经从200 μm光纤输出超过5 kW[77].

上述的常规合束、密集波长合束和光谱合束技术均为非相干合束，它是目前实现高功率半导体激光输出的主要方式.

2.4 相干合束

相干合束通过控制激光单元的波长、偏振及相位等，使各单元的光束相干输出，在远场获得高功率、高亮度激光. 理论上可耦合无限个激光单元，但由于该技术对激光单元的光谱、偏振及相位等都有严格要求，需对每个单元进行控制，并随着合束激光单元的增多，控制的难度也急剧上升，目前未实用化.

美国MIT于2011年报道通过种子注入控制激光单元光谱，相位反馈驱动电流控制相位，实现了218个激光单元相干合束，获得38.5 W功率输出[78]. 德国FBH于2015年报道利用锁相技术实现两个迷你bar相干合束，如图7所示，输出功率11.5 W，光束质量接近衍射极限[79]，其中，每个bar包含5个锥形激光单元.

3 展望

半导体激光器正向着高功率、高光束质量(高亮度)的方向快速发展，通过激光单元结构设计及模式限制，获得高光束质量激光输出，通过激光合束技术，实现千瓦、万瓦乃至更高功率. 已实现的360 W/0.6 mm mrad, 4680 W/4 mm mrad, 8000 W/6 mm mrad指标，达到了同功率下CO_2激光器和商用全固态激光器的输出水平，极大地推动了高功率半导体激光器从泵浦应用发展到直接应用，结合其小体积、轻重量、高转换效率及宽光谱输出等特性，将在材料加工、成像探测、医疗、显示等领域获得广泛应用. 在国防领域，半导体激光器将作为新一代小型化、轻量化的激光载荷光源，装备到车载、机载等机动性强的作战平台.

目前，我国在高端半导体激光芯片及合束光源方面与国外仍有一定差距. 需要进一步提高半导体激光芯片的功率和光束质量；攻克万瓦级激光合束和光纤组束技术；解决光栅制造关键技术；亟待联合国内优势单位进行攻关和突破，实现高端半导体激光器产品的自主研发和生产.

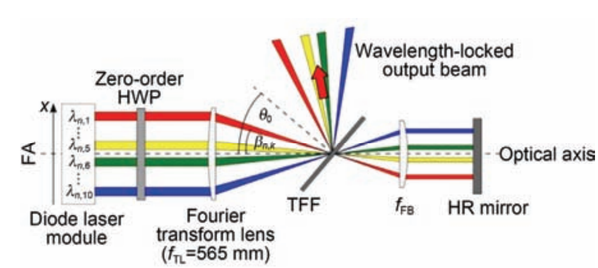

图 6 (网络版彩色)基于窄带滤光片的外腔反馈波长锁定结构

Figure 6 (Color online) Structure of feedback cavity with wavelength-locked by the narrowband filter

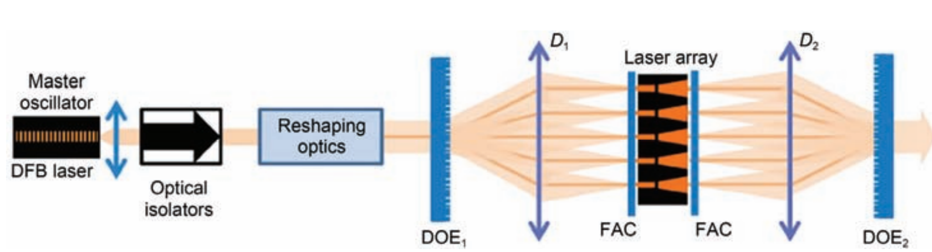

图 7 (网络版彩色)2 个迷你bar(5 个锥形激光单元)相干合束实验示意图

Figure 7 (Color online) CBC Experimental setup for two mini bar architecture with five MOPA emitters each

参考文献

1 Sverdlov B, Pfeiffer H U, Zibik E, et al. Optimization of fiber coupling in ultra-high power pump modules at λ=980 nm. Proc SPIE, 2013, 8605: 860508

2 Walpole J N, Donnelly J P, Taylor P J, et al. Slab-coupled 1.3-μm semiconductor laser with single-spatial large-diameter mode. IEEE Photonics Tech Lett, 2002, 14: 756–758

3 Huang R K, Donnelly J P, Missaggia L J, et al. High brightness slab-coupled optical waveguide lasers. Proc SPIE, 2007, 6485: 64850F

4 Huang R K, Chann B, Missaggia L J, et al. High-power coherent beam combination of semiconductor laser arrays. In: Proceedings of Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Application Systems Technologies. Optical Society of America, 2008

5 Dogana M, Smith G M, Missaggia L J, et al. Dense array slab-coupled optical waveguide laser capable of 500 W/bar. Proc SPIE, 2014, 8965: 89650L

6 Smith G M, Donnelly J P, Missaggia L J, et al. Slab-coupled optical waveguide lasers and amplifiers. Proc SPIE, 2012, 8241: 82410S

7 Schwertfeger S, Wiedmann J, Sumpf B, et al. 7.4 W continuous-wave output power of master oscillator power amplifier system at 1083 nm. Electron Lett, 2006, 42: 346–347

8 Wenzel H, Paschke K, Brox O, et al. 10 W continuous-wave monolithically integrated master-oscillator power-amplifier. Electron Lett, 2007, 43: 160–162

9 Lammert R M, Osowski M L, Elarde V C, et al. High-power single-mode laser diodes with tapered amplifiers. In: Proceedings of IEEE Lasers and Electro-Optics Society. Acapulco: IEEE, 2008. 850–851

10 Spiessberger S, Schiemangk M, Sahm A, et al. Micro-integrated 1 Watt semiconductor laser system with a linewidth of 3.6 kHz. Opt Express, 2011, 19: 7077–7083

11 Feise D, Blume G, Dittrich H, et al. High-brightness 635 nm tapered diode lasers with optimized index guiding. Proc SPIE, 2010, 7583: 75830V

12 Sumpf B, Adamiec P, Zorn M, et al. 650 nm tapered lasers with 1 W maximum output power and nearly diffraction limited beam quality at 500 mW. Proc SPIE, 2008, 6876: 68760M

13 Sumpf B, Adamiec P, Zorn M, et al. Nearly diffraction-limited tapered lasers at 675 nm with 1-W output power and conversion efficiencies above 30%. IEEE Photonics Tech Lett, 2011, 23: 266–268

14 Erbert G, Fricke J, Hülsewede R, et al. 3 W-high brightness tapered diode lasers at 735 nm based on tensile strained GaAsP-QWs. Proc SPIE, 2003, 4995: 29–38

15 Dittmar F, Sumpf B, Fricke J, et al. High-power 808-nm tapered diode lasers with nearly diffraction-limited beam quality of M^2=1.9 at P=4.4 W. IEEE Photonics Tech Lett, 2006, 18: 601–603

16 Fiebig C, Blume G, Kaspari C, et al. 12 W high-brightness single-frequency DBR tapered diode laser. Electron Lett, 2008, 44: 1253–1254

17 Müller A, Zink C, Fricke J, et al. 1030 nm DBR tapered diode laser with up to 16 W of optical output power. Proc SPIE, 2017, 10123: 101231B

18 Sumpf B, Hasler X H, Adamiec P, et al. 12.2 W output power from 1060 nm DBR tapered lasers with narrow spectral line width and nearly diffraction limited beam quality. In: Proceedings of European Conference on Lasers and Electro-Optics 2009 and the European Quantum Electronics Conference. CLEO Europe-EQEC, 2009

19 Winterfeldt M, Crump P, Knigge S, et al. High beam quality in broad area lasers via suppression of lateral carrier ac-cumulation. IEEE Photonics Tech Lett, 2015, 27: 1809–1812

20 Crump P, Winterfeldt M, Decker J, et al. Novel approaches to increasing the brightness of broad area lasers. Proc SPIE, 2016, 9767: 97671L

21 Bachmann A, Lauer C, Furitsch M, et al. Recent brightness improvements of 976 nm high power laser bars. Proc SPIE, 2017, 10086: 1008602

22 Kanskar M, Bao L, Chen Z, et al. Flared oscillator waveguide diodes (FLOW-diodes) enable high brightness fiber-coupled modules. In: Proceedings of the 25th International Semiconductor Laser Conference (ISLC). Kobe: IEEE, 2016

23 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. Proc SPIE, 2017, 10086: 1008609

24 Ledentsov N N, Shchukin V A. Novel concepts for injection lasers. Opt Eng, 2002, 41: 3193–3203

25 Ledentsov N N, Shchukin V A. Novel approaches to semiconductor lasers. Proc SPIE, 2002, 4905: 222–234
26 Maximov M V, Shernyakov Y M, Novikov I I, et al. Narrow vertical beam divergence laser diode based on longitudinal photonic band crystal waveguide. Electron Lett, 2003, 39: 1729–1731
27 Maximov M V, Shernyakov Y M, Novikov I I, et al. Low divergence edge-emitting laser with asymmetric waveguide based on one-dimensional photonic crystal. Phys Stat Sol C, 2005, 2: 919–922
28 Novikov I I, Gordeev N Y, Shernyakov Y M, et al. High-power single mode (>1 W) continuous wave operation of longitudinal photonic band crystal lasers with a narrow vertical beam divergence. Appl Phys Lett, 2008, 92: 103515
29 Shchukin V, Ledentsov N, Kalosha V, et al. Modeling of photonic crystal based high power high brightness semiconductor lasers. Proc SPIE, 2010, 7597: 75971A
30 Liu L, Qu H W, Liu Y, et al. High-power narrow-vertical-divergence photonic band crystal laser diodes with optimized epitaxial structure. Appl Phys Lett, 2014, 105: 231110
31 Rosales R, Kalosha V P, Posilovic K, et al. High brightness photonic band crystal semiconductor lasers in the passive mode locking regime. Appl Phys Lett, 2014, 105: 161101
32 Miah M J, Kettler T, Kalosha V P, et al. High temperature operation of 1060-nm high-brightness photonic band crystal lasers with very low astigmatism. J Sel Topics Quantum Electron, 2015, 21: 4900206
33 Rosales R, Roblot J, Kalosha V, et al. 1060-nm high brightness picosecond pulse generation in photonic band crystal lasers. IEEE Photonics Tech Lett, 2016, 28: 2086–2089
34 Wang L J, Tong C Z, Tian S C, et al. High-power ultralow divergence edge-emitting diode laser with circular beam. J Sel Topics Quantum Electron, 2015, 21: 1501609
35 Fricke J, Bugge F, Ginolas A, et al. High-power 980-nm broad-area lasers spectrally stabilized by surface bragg gratings. IEEE Photonics Tech Lett, 2010, 22: 284–286
36 Paschke K, Spießberger S, Kaspari C, et al. High-power distributed Bragg reflector ridge-waveguide diode laser with very small spectral linewidth. Opt Lett, 2010, 35: 402–404
37 Spießberger S, Schiemangk M, Wicht A, et al. DBR laser diodes emitting near 1064 nm with a narrow intrinsic linewidth of 2 kHz. Appl Phys B, 2011, 104: 813–818
38 Jia P, Chen Y Y, Zhang J W, et al. Broad-stripe single longitudinal mode laser based on metal slots. Opt Commun, 2016, 365: 215–219
39 Erbert G, Fricke J, Knauer A, et al. Design and realization of high-power DFB lasers. Proc SPIE, 2004, 5594: 110–123
40 Klehr A, Wenzel H, Brox O, et al. High-power 894 nm monolithic distributed-feedback laser. Opt Express, 2007, 15: 11364
41 Schultz C M, Crump P, Wenzel H, et al. Wide temperature range high power broad area 975nm DFB lasers. In: Proceedings of Conference on Lasers and Electro-Optics. Baltimore: Optical Society of America, 2009
42 Kanskar M, He Y, Cai J, et al. 50% efficient, >5 W, distributed feedback broad area laser (975 nm). In: Proceedings of Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies. Long Beach: Optical Society of America, 2006
43 Jang S J, Yu J S, Lee Y T. Laterally coupled DFB lasers with self-aligned metal surface grating by holographic lithography. IEEE Photonics Tech Lett, 2008, 20: 514–516
44 Gupta J A, Barrios P J, Aers G C, et al. 1550 nm GaInNAsSb distributed feedback laser diodes on GaAs. Electron Lett, 2008, 44: 578–579
45 Chen Y Y, Jia P, Zhang J, et al. Gain-coupled distributed feedback laser based on periodic surface anode canals. Appl Opt, 2015, 54: 8863–8866
46 Qin L, Liu Y, Ning Y Q, et al. Emission characteristics of surface second-order metal grating distributed feedback semiconductor lasers. Sci Bull, 2012, 57: 2083–2086
47 Hemenway M, Urbanek W, Dawson D, et al. Advances in high-brightness fiber-coupled laser modules for pumping multi-kW CW fiber lasers. Proc SPIE, 2017, 10086: 1008605
48 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. Proc SPIE, 2017, 10086: 1008609
49 Kasai Y, Yamagatab Y, Kaifuchi Y, et al. High-brightness and high-efficiency fiber-coupled module for fiber laser pump with advanced laser diode. Proc SPIE, 2017, 10086: 1008606
50 Yu H, Rossi G, Braglia A, et al. Development of a 300 W 105/0.15 fiber pigtailed diode module for additive manufacturing applications. Proc SPIE, 2017, 10086: 100860A
51 Xu D, Guo Z J, Zhang T J, et al. 600 W high brightness diode laser pumping source. Proc SPIE, 2017, 10086: 1008603
52 Timmermann A, Bartoschewski D, Schlüter S, et al. Intensity increasing up to 4 MW/cm^2 with BALB's via wavelengths coupling. Proc SPIE, 2009, 7198: 71980X

53 Voß M, Meinschien J, Bruns P, et al. High brightness fibre coupled diode lasers of up to 4-kW output power for material processing. Proc SPIE, 2012, 8241: 824103
54 Köhler B, Kissel H. High-power, high-brightness and low-weight fiber coupled diode laser device. Proc SPIE, 2011, 7918: 79180O
55 Köhler B, Unger A, Kissel H, et al. Multi-kW high-brightness fiber coupled diode laser. Proc SPIE, 2013, 8605: 86050B
56 Strohmaier S, Tillkorn C, Olschowsky P, et al. High-power, high-brightness direct-diode LASERS. OPN Optics Photonics News, 2010, 21: 25–29
57 Kissel H, Wolf P, Bachmann A. et al. Tailored bars at 976 nm for high-brightness fiber-coupled modules. Proc SPIE, 2017, 10086: 100860B
58 Könning T, Köhler B, Wolf P, et al. Optical components for tailoring beam properties of multi-kW diode lasers. Proc SPIE, 2017, 10085: 100850G
59 Krause V, Koesters A, Koenig H, et al. Brilliant high-power diode lasers based on broad area lasers. Proc SPIE, 2008, 6876: 687615
60 Malchus J, Krausea V, Koesters A, et al. A 25 kW fiber-coupled diode laser for pumping applications. Proc SPIE, 2014, 8965: 89650B
61 Malchus J, Krause V, Rehmann G, et al. A 40 kW fiber-coupled diode laser for material processing and pumping applications. Proc SPIE, 2015, 9348: 934803
62 Decker J, Crump P, Fricke J, et al. 25-W monolithic spectrally stabilized 975 nm minibars for dense spectral beam combining. IEEE Photonics Tech Lett, 2015, 27: 1675–1678
63 Witte U, Traub M, Meo A D, et al. Compact 35 μm fiber coupled diode laser module based on dense wavelength division multiplexing of NBA mini-bars. Proc SPIE, 2017, 9733: 97330H
64 Unger A, Uthoff R, Stoiber M, et al. Tailored bar concepts for 10 mm-mrad fiber coupled modules scalable to kW-class direct diode lasers. Proc SPIE, 2015, 9348: 934809
65 Witte U, Schneider F, Holly C, et al. kW-class direct diode laser for sheet metal cutting based on commercial pump modules. Proc SPIE, 2017, 10086: 1008608
66 Heinemann S, Fritsche H, Kruschke B, et al. Compact high brightness diode laser emitting 500 W from a 100 μm fiber. Proc SPIE, 2017, 8605: 86050Q
67 Fritsche H, Krusche B, Koch R, et al. High brightness, direct diode laser with kW output power. Proc SPIE, 2014, 8965: 89650G
68 Fabio F, Haro F, Andreas G, et al. Building block diode laser concept for high brightness laser output in the kW range and its applications. Proc SPIE, 2016, 9730: 97300G
69 Hengesbach S, Krauch N, Holly C, et al. High-power dense wavelength division multiplexing of multimode diode laser radiation based on volume Bragg gratings. Opt Lett, 2013, 38: 3154–3157
70 Daneu V, Sanchez A, Fan T Y, et al. Spectral beam combining of a broad-stripe diode laser array in an external cavity. Opt Lett, 2000, 25: 405–407
71 Chann B, Huang R K, Missaggia L J, et al. Near-diffraction-limited diode laser arrays by wavelength beam combining. Opt Lett, 2005, 30: 2104–2106
72 Gopinath J T, Chann B, Fan T Y, et al. 1450-nm high-brightness wavelength-beam combined diode laser array. Opt Express, 2008, 16: 9405–9410
73 Huang R K, Bien C, James B, et al. Teradiode's high brightness semiconductor lasers. Proc SPIE, 2016, 9730: 97300C
74 Hecht J. Beam combining cranks up the power. Laser Focus World, 2012, 48: 41–43
75 Zimer H, Haas M, Ried S, et al. Thin film filter wavelength-locked laser cavity for spectral beam combining of diode laser arrays. In: Proceedings of 2014 IEEE Photonics Conference. San Diego: IEEE, 2014. 230–231
76 Zimer H, Haas M, Nagel S, et al. Spectrally stabilized and combined diode lasers. In: Proceedings of 2015 IEEE High Power Diode Lasers and Systems Conference (HPD). Coventry: IEEE, 2015. 31–32
77 Strohmaier S G, Erbert G, Meissner-Schenk A H, et al. kW-class diode laser bars. Proc SPIE, 2017, 10086: 100860C
78 Redmond S M, Creedon K J, Kansky J E. Active coherent beam combining of diode lasers. Opt Lett, 2011, 36: 999–1001
79 Schimmel G, Janicot S, Hanna M, et al. Coherent beam combining architectures for high power tapered laser arrays. Proc SPIE, 2017, 10086: 100860O

Summary for “高功率、高光束质量半导体激光器研究进展”

Advances in high power high beam quality diode lasers

ZHANG Jun[1,2], CHEN YongYi[1,2†], QIN Li[1,2†], PENG HangYu[1,2*], NING YongQiang[1,2] & WANG LiJun[1,2]

[1] *Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China;*
[2] *State Key Laboratory of Luminescence and Applications, Changchun 130033, China*
† Equally contributed to this work
* Corresponding author, E-mail: penghy@ciomp.ac.cn

Semiconductor laser enjoys its benefits such as small volume, light weight, long operation life, various selectable wavelength and direct current driving, meanwhile suffers from its beam quality which is making it hard for direct applicdations. Researchers around the world realize that it is beam quality has the same importance as power, and acquiring high power and high beam quality is the key issue in semiconductor laser induxtry. The question of how to improve the beam quality of high power semiconductor lasers is attracting increasing attention from researchers home and abroad. Considering the application fields which require high power high beam quality, such as industry processing and national defense, this paper discussed the research progress on both diode laser unit devices and laser beam combining sources. First of all, the relationships between single laser emitter’s structureand themodeof laser units, including lateral mode, transverse mode and longitudinal mode, are analyzed. Lateral mode is the main factor which limits the high beam quality for high power semiconductor lasers. Ridge waveguide is the main method adopted to realize single lateral mode. A method called longitudinal photonic bandgap crystal is introduced to manipulate the transverse mode of a single laser unit, which can acquire large optical near field and high beam quality even in high current input. To control longitude mode, usually to acquire single longitude mode in single semiconductor laser unit, distribute Bragg reflectors and distribute feedback structures using gratings in fabrication is also introduced in this section. And then we summarize the methods and some results of controlling modeusedinternationalresearchers. Further more, we introduced the lasers beam technology, including beam shaping and beam combining, considering all conditions of single emitters beam combining, mini bar beam combining, centimeter bar beam combining, laser stacks beam combining and laser systems beam combining. In beam combining technology, we introducted the method of traditional beam combining, including polarizetion beam combining and wavelength beam combining. Then the method of using dense wavelength division multiplexing with volume Bragg gratings to realize beam combinign is also introduced. Spectrum beam combining method using a Bragg diffractive grating is then introduced, which may realize a high beam quality of a single emitter’s beam spot with a laser bar’s optical power. Furthermore, coherent beam combining considering each laser unit’s wavelength, polarization and phase to realize high power high intensity farfield is also introduce. Then, the lastest international reported of high power, high beam quality diode laser combining sources are introduced, and characteristics of laser beam technology and development trends arediscussed and analyzed. Finally, the developments of high power high beam quality diode lasers are prospected. Right now, our country still have a distance below internal research in high quality semiconductor laser chip and beam combining source. The semiconductor laser chips’ power and beam quality needed to be improved. The technology of 10 kW level beam combining and optical fiber coupling technology is still urged to be acquired. Grating fabrication in optical beam combining technology and chip fabrication are also needed to be conquered.

diode laser, high power, high beam quality, laser beam combining

doi: 10.1360/N972017-00352