

分离反射式中继成像光谱合束光源

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摘要 光谱合束是提升高功率半导体激光器光束质量和亮度的关键技术之一。增加激光单元数量是提升光谱合束功率的主要途径,但同时造成合束光学元件尺寸变大,激光谐振腔变长不利于光谱合束光源的实际应用。提出了分离反射式中继成像光谱合束结构,将大尺寸中继成像镜分解成小尺寸的柱面反射镜阵列,每个激光线阵独立成像。最终 12 个激光线阵共计 228 个激光单元的光谱合束的输出激光功率为 442.9 W,电光转换效率为 41.8%,光谱范围为 777.12~811.28 nm,光参量为 4.00 mm×mrad,与单元激光接近。所提结构为多激光单元光谱合束提供了一种可行方案,有利于激光器的工程应用。

关键词 激光器; 半导体激光器; 光谱合束; 分离反射式中继成像; 高功率

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1 引言

面向激光远距离照明和激光无线传能的应用需求,考虑到大气窗口以及光电探测器和接收装置的高响应波段等前提条件,800 nm 波段、高功率、高光束质量半导体激光器是满足该应用需求的优选光源之一^[1-2]。但受材料体系和结构的限制,该波段器件存在单元功率低、光束质量差等缺点,其应用受影响^[3-4]。光谱合束(SBC)是高功率半导体激光器实现高光束质量、高亮度激光输出的最有效合束技术之一^[5-7]。国内外在 900 多纳米波段开展了大量的光谱合束光源研究,证明了该技术的有效性,并已经将 900 多纳米波段的半导体激光器成功应用于激光加工等领域^[8-12]。800 nm 波段的光谱合束研究相对较少,中国科学院长春光学精密机械与物理研究所在该波段开展了光谱合束光源的系列研究^[13-15],并已实现了 10 个激光线阵合束输出数百瓦的合束激光^[15]。

为了提高光谱合束功率,需要进一步增加激光单元数量,但这会造成合束光学元件尺寸的增大,导致激光合束光路增加。在之前报道的 10 个激光线阵光谱合束中,所采用的变换透镜尺寸在光谱合束方向上超过 100 mm,且整个谐振腔的物理尺寸达到数米,这无疑为光学元件加工、谐振腔装调以及激光器使用等方面带来不便。通过中继成像镜可以减小激光器的物理

尺寸^[14],但同样存在光学元件偏大的问题。因此,除了在光谱上进行密集光谱合束外,在结构上也需要进一步压缩,以便于激光器的工程应用。

本文提出了分离反射式中继成像光谱合束结构,将大尺寸的中继成像镜分解成多个小尺寸的反射式中继成像镜组合,然后通过共同的变换透镜将所有激光单元投影到光栅上,结合外腔镜,实现了多激光单元的光谱合束。通过该方法,在 777~813 nm 波段范围内,12 个激光线阵共计 228 个激光单元的光谱合束在 50 A 电流的驱动下,连续输出功率为 442.9 W,电光转换效率为 41.8%,光参量为 4.00 mm×mrad。所提结构为多激光单元光谱合束提供了有效技术途径。

2 基本原理

分离反射式中继成像光谱合束结构如图 1 所示,其中 n 为每个激光线阵上的单元数量, λ_{-1n} 为激光线阵 LDA₋₁ 上 n 个激光单元的输出波长, λ_{+1n} 为激光线阵 LDA₊₁ 上 n 个激光单元的输出波长,OC 为输出耦合镜。以三个半导体激光线阵(LDA)光谱合束为例,为了便于说明,以下 LDA 的输出方向特指该 LDA 中心位置激光单元的出射方向。位于中间位置的 LDA₀ 的输出方向与合束光路的光轴(OZ)方向重合,LDA₁和LDA₋₁对称分布于光轴两侧,其输出方向与

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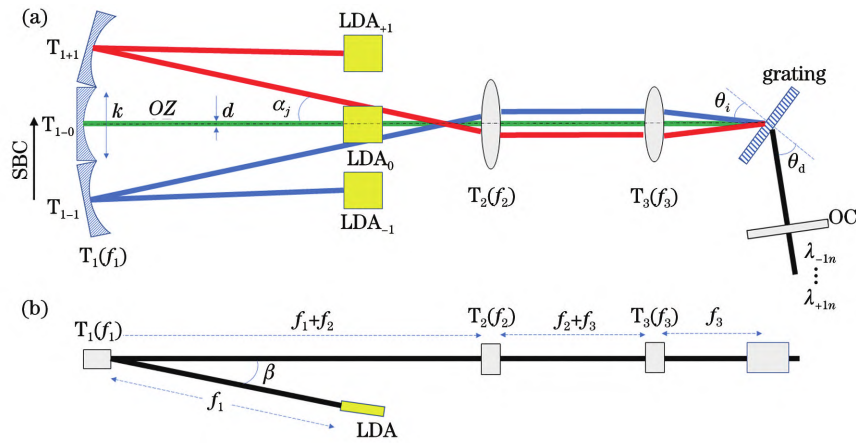


图 1 分离反射式中继成像光谱合束结构示意图。(a)光谱合束方向;(b)非光谱合束方向

Fig. 1 Structural diagram for SBC based on separated reflection relay imaging. (a) SBC direction; (b) non-SBC direction

OZ 分别成角度 α_1 和 α_{-1} 。LDA 首先经过准直,然后入射到柱面反射镜(T_1)上。柱面反射镜 T_1 和柱透镜 T_2 构成中继成像结构,将 LDA 转换成缩小的像,该像经过柱透镜 T_3 入射到衍射光栅上,并在光栅上重叠,垂直于光栅衍射方向的外腔镜使合束激光的一部分返回到激光单元中形成谐振,另一部分直接输出形成激光。激光单元 i 具有不同的光栅入射角 θ_i 和相同的衍射角 θ_d ,使得每个激光单元在不同中心波长处谐振,因此外腔镜输出了谱宽($\Delta\lambda$)被拓宽、功率为单元光束功率之和、光束质量与激光单元光束质量相近的合束激光。线阵前腔面、柱面反射镜 T_1 (焦距为 f_1)、柱透镜 T_2 (焦距为 f_2)、柱透镜 T_3 (焦距为 f_3) 和衍射光栅的位置关系如图 1 所示。其中,共有 $2N+1$ 个 LDA 对称分布于中心光轴两侧,位于中心位置的激光线阵为 LDA_0 ,位于两侧的激光线阵分别为 $LDA_{-N}, LDA_{(-N-1)}, \dots, LDA_{-1}$ 和 $LDA_{+1}, \dots, LDA_{+(N-1)}, LDA_{+N}$ 。柱面反射镜 T_1 由焦距相同的系列小柱面反射镜 $T_{1-N}, \dots, T_{1-1}, T_{1-0}, T_{1+1}, \dots, T_{1+N}$ 组合而成,每个小柱面反射镜对应一个 LDA,并且其光轴方向与相应的 LDA 出射方向重合。为了不遮挡光路,LDA 入射到 T_1 时在非光谱合束方向上与光轴 OZ 成一个夹角 β ,在封装要求下,该角度越小越好。所采用的色散元件为 -1 级透射式衍射光栅,位于中心位置的激光线阵 LDA_0 的入射角 θ_0 和衍射角 θ_d 满足 $\theta_0 = \theta_d = \theta_{\text{Littrow}} = \arcsin[\lambda/(2\Lambda)]$,其中 θ_{Littrow} 为衍射光栅的利特罗角, λ 为光栅的设计波长, Λ 为光栅的空间周期。为了减小腔内其他耦合腔效应,腔内的光学元件及线阵的前腔面均镀有增透膜。

当耦合线阵数量为 $2N+1$ (N 为自然数) 个时,第 j 个激光线阵 LDA_j 的光轴偏离夹角 α_j 与柱面反射镜 T_1 焦距 f_1 和空间周期 k 有关:

$$\alpha_j = 2 \cdot N \cdot \arctan\left(\frac{k}{2 \cdot f_1}\right). \quad (1)$$

单个线阵经过该结构后的谱宽 $\Delta\lambda_s$ 为

$$\Delta\lambda_s = \frac{f_2 \cdot \Lambda \cdot d}{f_1 \cdot f_3} \cdot \cos \theta_{\text{Littrow}}, \quad (2)$$

式中: d 为单个线阵在光谱合束方向上的光斑宽度。

$(2N+1)$ 个 LDA 以相同空间周期 k 关于光轴对称排列,则对应的整体线宽 $\Delta\lambda_T$ 为

$$\Delta\lambda_T = \frac{f_2 \cdot \Lambda \cdot (2 \cdot N \cdot k + d)}{f_1 \cdot f_3} \cdot \cos \theta_{\text{Littrow}}. \quad (3)$$

上述是耦合线阵数量为奇数时的情况。当耦合的线阵数量为偶数 $2N$ 时,对应的 LDA_j 的光轴偏离夹角 α_j 则为

$$\alpha_j = (2 \cdot N - 1) \cdot \arctan\left(\frac{k}{2 \cdot f_1}\right). \quad (4)$$

对应的整体线宽为

$$\Delta\lambda_T = \frac{f_2 \cdot \Lambda \cdot [(2 \cdot N - 1) \cdot k + d]}{f_1 \cdot f_3} \cdot \cos \theta_{\text{Littrow}}. \quad (5)$$

为了使光束被有效利用,要求 $k \geq d$,这样光均能完全落在柱面反射镜 T_1 的口径内,但是过大的 k 会导致合束光谱展宽,因此,在保证合适装调条件下, k 尽量接近 d 。

基于上述结构,采用 12 个 LDA 进行光谱合束。单个 LDA 包含 19 个激光单元,周期为 $500 \mu\text{m}$,单元发射孔径慢轴方向尺寸为 $100 \mu\text{m}$,慢轴发散角为 8° ,填充因子为 20%,腔长为 2 mm,偏振态为横电(TE),前腔面镀增透膜,腔面反射率 $< 0.5\%$ 。所采用的透射光栅刻线密度为 1765 line/mm,设计波长为 800 nm, θ_{Littrow} 为 44.93° ,色散系数为 2.49 mrad/nm,对 TE 线偏振光的负一级衍射效率最高为 94%,在 770~830 nm 波段范围内的负一级衍射效率 $> 90\%$ 。

为了减小激光器的物理尺寸,所采用的中继成像镜组 T_1 和 T_2 的焦距 f_1 和 f_2 分别为 200 mm 和 20 mm,变换透镜焦距 f_3 为 190 mm,等效焦距为 1.9 m,激光芯片出光端面与透射光栅的物理距离由之前的 3.80 m 降至 0.82 m。由于采用了反射折叠结构,在光谱合束方向上,激光芯片被折叠到腔内,尺寸被进一步压缩至 0.62 m。受封装尺寸影响,非光谱合束方向上的夹角 β 为 3° 。同时,为了减小激光线阵之

间的不发光区,柱面反射镜 T_1 在光谱合束方向上满口径工作,柱面反射镜 T_1 在光谱合束方向上的尺寸为 10 mm,为了保留一定的装调位置,柱面反射镜 T_1 在光谱合束方向上的空间周期为 11 mm。

3 分析与讨论

单个 LDA 自由运行下的功率曲线及 12 个 LDA 光谱合束后的功率、效率和电压随电流的变化如图 2 所示。当热沉温度为 20 °C 时,单个线阵自由运行下的阈值电流为 15 A,50 A 电流驱动下的输出功率为 35.2 W。在 12 个 LDA 光谱合束后,由于外腔反馈作用,阈值电流降至 7 A,在电流 50 A、电压 21.2 V 驱动下,连续输出功率为 442.9 W,电光转换效率为 41.8%,整体斜率效率为 10.8 W/A,平均每个 LDA 的斜率效率为 0.9 W/A。

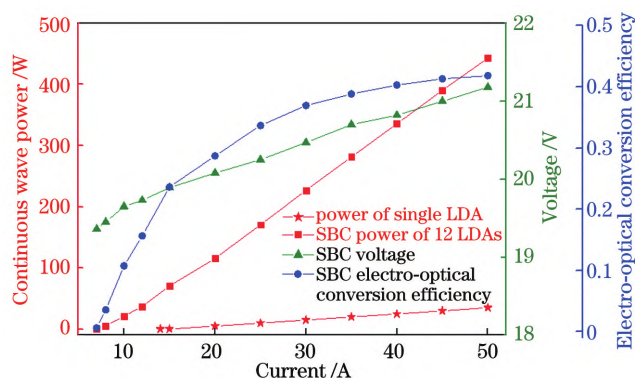


图 2 12 个 LDA 光谱合束后的输出功率、电压和效率曲线
Fig. 2 Output power, voltage, and efficiency curves for 12 LDAs after SBC

50 A 电流驱动下的合束输出光谱如图 3 所示。整体光谱范围为 777.12~811.28 nm,光谱宽度为 34.16 nm,可以看到 12 个间隔分明的光谱带,对应 12 个线阵。各个光谱带之间的相对强度较为一致,高度差别不超过 20%,说明每个线阵均能实现很好的光谱锁定和谐振。

在 20 A 电流驱动下,单个线阵的精细光谱测试结果如图 4 所示,可以看到明显的 19 个增益峰值,其与

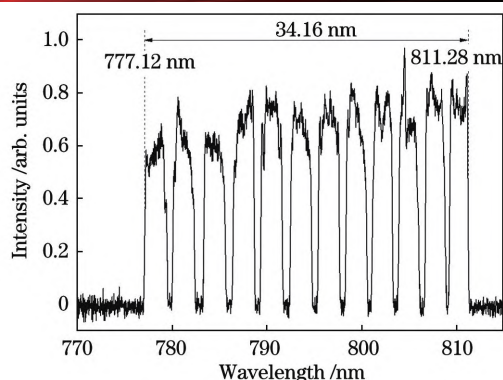


图 3 12 个 LDA 光谱合束后在 50 A 电流驱动下的输出光谱
Fig. 3 Output spectrum of 12 LDAs driven by 50 A current after SBC

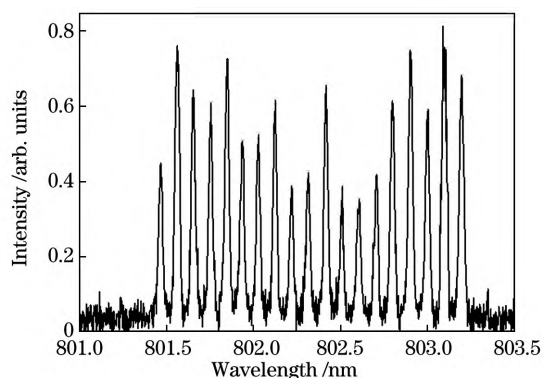


图 4 单个 LDA 的输出光谱
Fig. 4 Output spectrum of single LDA

线阵上的激光单元相对应,说明均实现了有效锁定。但是各激光单元的峰值强度存在较大差别,峰值强度最小值与最大值的比值接近 50%,这与各个激光单元被锁定后的谐振强度直接相关,受线阵芯片弯曲笑脸现象(Smile)、每个激光单元的起振阈值、微透镜缺陷及装调精度等多个因素影响。

合束前后的光场分布照片如图 5 所示,电流为 20 A,水平方向为光谱合束方向。其中,图 5(a)位于中继成像镜 T_1 后,光场为多个激光单元在光谱合束方向上的叠加,水平光斑尺寸大;图 5(b)位于外腔镜后,所有单元激光重叠在一起形成单个光斑,水平尺寸减小。

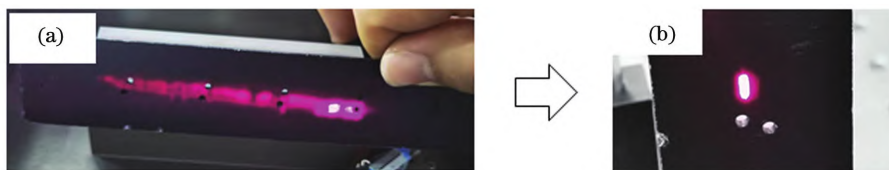


图 5 合束前后的光场分布。(a)前;(b)后

Fig. 5 Distributions of light field before and after SBC. (a) Before; (b) after

合束后的光束质量如图 6 所示。测试电流为 50 A,测试仪器为光束质量分析仪,采用焦距为 18.75 mm 的非球面聚焦镜聚焦,扫描测试焦点前后的光场分布,以二阶矩方法评价,拟合后整体的光参量积为 4.00 mm×mrad,接近激光单元的光参量积 3.50 mm×mrad。相对于激光单元的光束质量,整体

光束质量存在一定恶化,主要原因包括三方面:1)激光光线阵封装问题(如指向不一致性、Smile 等)。在高电流驱动下出现一定的自激射,合束激光两侧存在一定的拖尾现象,恶化光束质量。2)光学系统像差问题。尤其是随着线阵数量的增加,光谱合束方向上的尺寸增大,合束光谱变宽,受球差、彗差及色差等影响,入射到光栅上

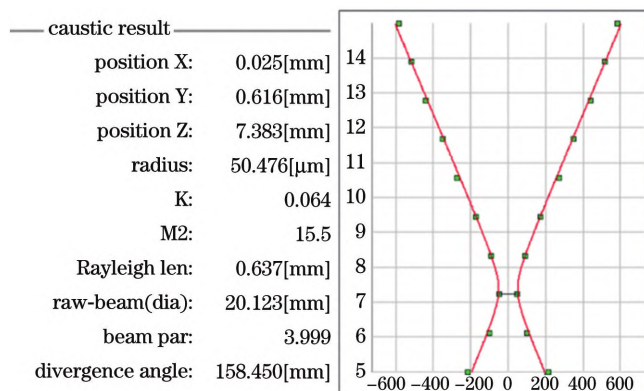


图6 合束后的光束质量

Fig. 6 Beam quality after SBC

的光斑不能很好地重叠在一起,导致光谱合束后的光束质量变差。3) 光学元件(包括微透镜、成像镜、光栅等)的热形变。高功率工作时其面型和位置的轻微变化将导致谐振特性变差,微透镜位置的影响尤为显著。

4 结 论

针对数量多的激光单元光谱合束,提出了分离反射式中继成像光谱合束结构。通过柱面反射镜阵列组合,将大尺寸光学元件小型化、分散化,12个激光线阵共计228个激光单元实现了单腔光谱合束,合束功率达到442.9 W,电光转换效率达到41.8%,光参量为 $4.00\text{ mm} \times \text{mrad}$,与单元激光光束质量接近。所提结构为多激光单元光谱合束结构的小型化提供了可行的技术途径。下一步将通过偏振合束,直接倍增激光功率,同时结合光纤耦合技术,实现芯径为 $50 \sim 100\text{ }\mu\text{m}$ 的光纤耦合输出千瓦级800 nm波段功率,对接工程应用。

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Spectral Beam Combining of Diode Lasers Based on Separated Reflection Relay Imaging

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Abstract

Objective 800 nm diode lasers with high power and high beam quality are the recommended laser sources for long-

distance laser illumination and laser wireless energy transfer applications. However, due to the restrictions of material gain and epitaxial structure, 800 nm diode lasers have the drawbacks of relatively low power and poor beam quality. Spectral beam combining (SBC) is one of the most dependable beam combining techniques for high-power diode lasers to achieve high beam quality and high brightness. SBC in an external cavity feedback configuration has been implemented with success in the 800–900 nm band. In order to increase the SBC power, it is necessary to further increase the numbers of laser units, but this will lead to the increase of the size of optical components and the length of optical path, which brings great difficulties for installation and adjustment. The physical size of the SBC laser can be lowered by adding the relay imaging structure, but the issue of the huge size of optical elements also exists. Especially for the SBC source with the combining number of over 10 diode laser arrays (LDAs), the output pointing of each LDA is susceptible to be inconsistent due to packaging, micro lens assembly, and other factors. Moreover, the conventional relay imaging structure cannot be optimized for each LDA, and the SBC performance will be significantly reduced, including the power, beam quality, and efficiency.

Methods An SBC structure with separated reflection relay imaging is suggested (Fig. 1). The large-size relay imaging lens is decomposed into a combination of multiple small-size cylindrical mirrors with the same focal length as that of the large-size lens. Each cylindrical mirror matches a specific LDA, and its optical axis aligns with the corresponding LDA emission direction. By modifying the cylindrical mirror, the separated relay imaging structure can compensate for the pointing inconsistency and optical aberration to a certain extent, achieving good SBC performances.

Results and Discussions 12 LDAs with the front facet reflectivity of $<0.5\%$ are employed for SBC. Each LDA consists of 19 transverse electric (TE) polarization emitters with a filling factor of 20% , a pitch of $500\text{ }\mu\text{m}$, a cavity length of 2 mm , and a slow axis divergence angle of 8° . The focal lengths f_1 , f_2 , and f_3 of the cylindrical lenses T_1 , T_2 , and T_3 are 200 mm , 20 mm , and 190 mm , respectively. The equivalent focal length of the transformation lens is 1.9 m . Compared with the conventional SBC structure, the physical distance between the front facet of LDA and the grating decreases from 3.8 m to 0.82 m . The cylinder lens T_1 is composed of 12 tiny cylinder mirrors with an aperture of 10 mm and a spatial period of 11 mm in the SBC direction. The negative first-order transmission grating is used as the dispersive element with the period (Λ) of 1765 line/mm , wavelength of 800 nm , and Littrow angle of 44.93° . The negative first-order diffraction efficiency is $>90\%$ in the range of $770\text{--}830\text{ nm}$ for S polarized light. After SBC, the threshold current is reduced from 15 A to 7 A with the help of external feedback. Driven by 50 A current and 21.2 V voltage, the continuous wave (CW) power, the electro-optic conversion efficiency, the overall slope efficiency, and the average slope efficiency of each LDA are 442.9 W , 41.8% , 10.8 W/A , and 0.9 W/A , respectively (Fig. 2). The whole spectral range is from 777.12 nm to 811.28 nm and the spectral width is 34.16 nm (Fig. 3). 12 spaced spectral bands can be observed, matching 12 LDAs. The relative intensity of each spectral band is relatively consistent, and the height difference is no more than 20% , indicating that each LDA achieves good spectral locking and resonance. After being focused by an aspherical lens with a focal length of 18.75 mm , the intensity distributions before and after the focus are measured and assessed using the second-order moment method. After fitting, the whole beam parameter product is $4.00\text{ mm}\times\text{mrad}$ (Fig. 6), close to that of a single emitter of $3.50\text{ mm}\times\text{mrad}$.

Conclusions Aiming at the SBC of a large number of laser units, an SBC structure based on separated reflection relay imaging is demonstrated. The huge-size optical element is miniaturized and divided into several small-size elements. SBC of 12 LDAs with 228 emitters is realized by a single external cavity, with the CW power of 442.9 W , the electro-optic conversion efficiency of 41.8% , and the beam parameter product of $4.00\text{ mm}\times\text{mrad}$. This offers a viable technical method for the miniaturization of the SBC structure. The next step is to directly multiply the laser power through polarization beam combination, and the fiber coupling technology will be combined to realize the 800 nm power output of kilowatt-level with the core diameter of $50\text{--}100\text{ }\mu\text{m}$, convenient for real applications.

Key words lasers; diode lasers; spectral beam combining; separated reflective relay imaging; high power