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160W端面抽运正支混合腔板条激光器的研究

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研究了 LD 端面抽运 Nd:YVO_4 板条晶体正支混合腔 Innoslab 结构的激光器. 利用 Innoslab 激光器的功率升级简单的优点, 采用尺寸为 22 mm × 10 mm × 1 mm 的大块 Nd:YVO_4 晶体, 最终在抽运功率为 462 W 时, 获得最大功率为 160 W 的连续激光输出, 功率波动为 2.6%, 光-光转换效率和斜效率分别为 41.5% 和 47.7%. 在输出功率为 145 W 时, 测得光束质量在稳腔和非稳腔方向上分别为 2.21 和 1.37.

关键词: Nd:YVO_4 晶体, 正支混合腔, Innoslab

PACS: 42.55.–f, 42.55.Xi, 42.60.–v, 42.60.Da **DOI:** 10.7498/aps.65.194206

1 引 言

自激光问世以来, 由于其自身的优点而被广泛地应用于工业、医疗、军事等领域[1−3]. 高功率高光束质量激光器一直为人们所追求, 传统棒状固体激光器在高功率运转下, 会出现明显的热透镜和热双折射等效应, 这些都严重影响了输出激光的光束质量. 1998 年, 德国弗朗禾费研究所 Du 等 [4] 提出部分端面抽运混合腔板条激光器结构 (即 Innoslab laser), 因其结构紧密, 良好的热处理性能和功率升级简单等优点而得到广泛的关注和应用[5−8].

近年来, 随着研究人员的不断努力, 高功率高光束质量的 Innoslab 激光器不断涌现出来. 2003 年, Shi 等[9] 用 Nd:YVO_4 晶体最高获得了 110 W 激光输出, 光束质量因子在稳腔和非稳腔方向上分别为 1.5 和 1.3; 2010 年, Cui 等[10] 采用上能级直接抽运的方式获得 126.7 W 的激光输出, 在稳腔和非稳腔方向光束质量分别为 1.15 和 1.1. 2012 年, 毛叶飞等[11] 用双端抽运 Nd:YVO_4 晶体的方法获得 202 W 的输出功率, 稳腔和非稳腔方向光束质量因子分别为 2.25 和 1.72. 2015 年, Mao 等[12] 利用 14 mm × 10 mm × 1 mm 的 Nd:YVO_4 晶体获得了 134 W 的输出, 稳腔和非稳腔方向光束质量因子分别为 2.1 和 1.7.

在本实验中, 我们采用的 Nd:YVO_4 晶体的大小为 22 mm × 10 mm × 1 mm, 结合正支混合腔结构, 在抽运功率为 462 W 的情况下, 获得最大功率为 160 W 的连续激光稳定输出, 功率波动为 2.6%, 光-光转换效率和斜效率分别为 41.5% 和 47.7%. 在输出功率为 145 W 时, 测得光束质量在稳腔和非稳腔方向上分别为 2.21 和 1.37.

2 实验装置

如图 1 所示, 实验装置主要包括: 抽运源、整形系统、谐振腔三部分. 抽运源由 6 个 bar 条组成, 输出抽运光的中心波长为 808 nm, 每个 bar 条都自带微透镜准直, 使输出抽运光在快方向上基本为平行光. 整形系统是由两组柱面镜, 一个矩形波导和一个聚焦透镜组成, 其中矩形波导起到混束的作用, 使抽运光均匀. 抽运光通过整形系统被整形成大小约 22 mm × 0.4 mm 的矩形抽运线, 并耦合到 Nd:YVO_4 晶体中, 整形系统损耗大约为 12%. Nd:YVO_4 晶体的掺杂浓度为 0.3 at.%, 两个通光端面 (22 mm × 1 mm) 抛光, 并

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镀有对1064 nm和808 nm 高透膜. 晶体的吸收效率为95%. 晶体的两个大面(22 mm × 10 mm)作为冷却面, 通过真空钎焊将金属铟焊接到晶体和紫铜热沉上. 紫铜热沉和带有微通道的半导体激光二极管同时用循环的恒温冷却水进行冷却, 水温为23 °C. 谐振腔由M1和M2组成, M1 为半径为$R1 = 500$ mm的球面镜, 并镀有对1064 nm高反和808 nm高透的介质膜; M2为半径为$R2 = -350$ mm柱面镜, 并镀有对1064 nm高反的介质膜. 在水平方向, 腔镜M1和M2构成离轴正支共焦非稳腔; 在竖直方向, 腔镜M1和M2构成凹平稳腔, 腔长$L = (R1 + R2)/2 = 75$ mm, 等效透过率$T = 1 - |R2|/R1 = 30\%$.

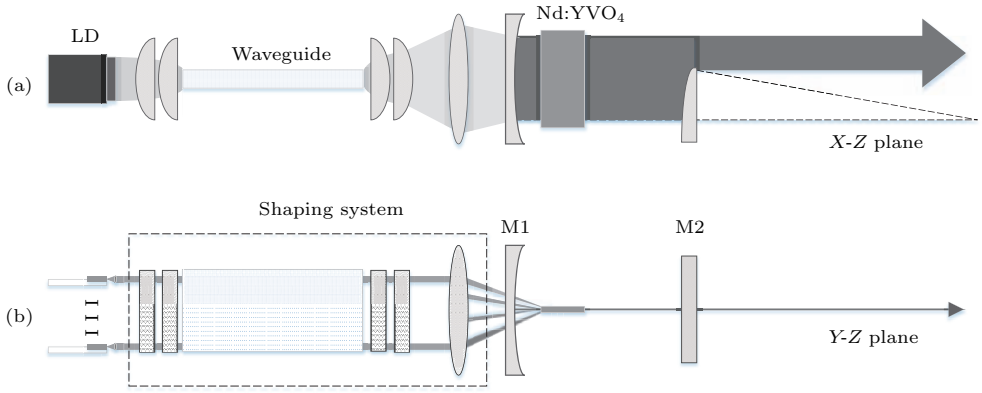


图1 LD端面抽运混合腔Nd:YVO_4板条激光器实验装置示意图 (a)非稳腔方向; (b)稳腔方向

Fig. 1. The schematic of LD end-pumped Nd:YVO_4 slab laser: (a) Unstable direction; (b) stable direction.

3 实验结果与讨论

实验中输出功率随抽运功率变化的趋势如图2所示, 当抽运功率为462 W时获得160 W的连续激光输出, 光-光转化效率和斜效率分别为41.5%和47.7%. 图3是在15 min内测量输出功率稳定性示意图, 功率波动为2.6%.

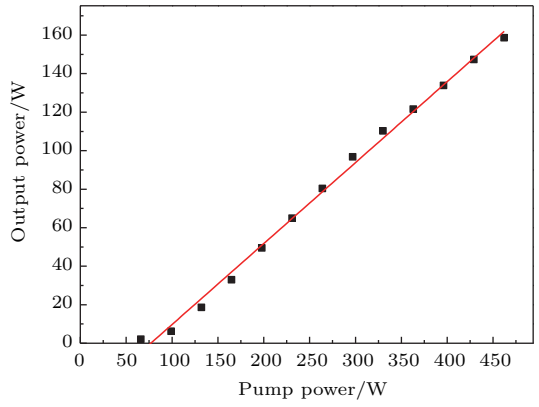


图2 激光输入输出功率示意图

Fig. 2. The output power versus the incident pumped power.

在输出功率为145 W时, 测量输出激光的光束质量M^2因子, 用半径为300 mm的球面镜对输出激光聚焦, 然后利用CCD相机测量束腰附近不同位置处光斑半径大小, 然后再利用式

$$M^2 = \frac{\pi d_0^2}{4\lambda z}\sqrt{\frac{d^2(z)}{d_0^2} - 1}$$

进行拟合, 其中z表示到束腰处的距离, $d(z)$处光斑半径, d_0为束腰半径, λ为波长. 分别在非稳腔方向和稳腔方向测量多组数据进行二次拟合, 最终得到拟合数据及其远场光斑如图4所示, 光束质量因子在非稳腔方向和稳腔方向分别为1.37和2.21.

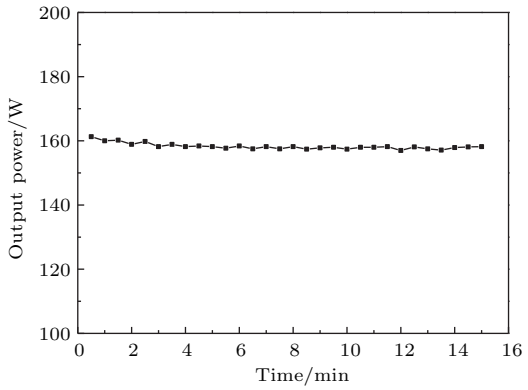


图3 输出功率稳定性示意图

Fig. 3. The stability of the output power.

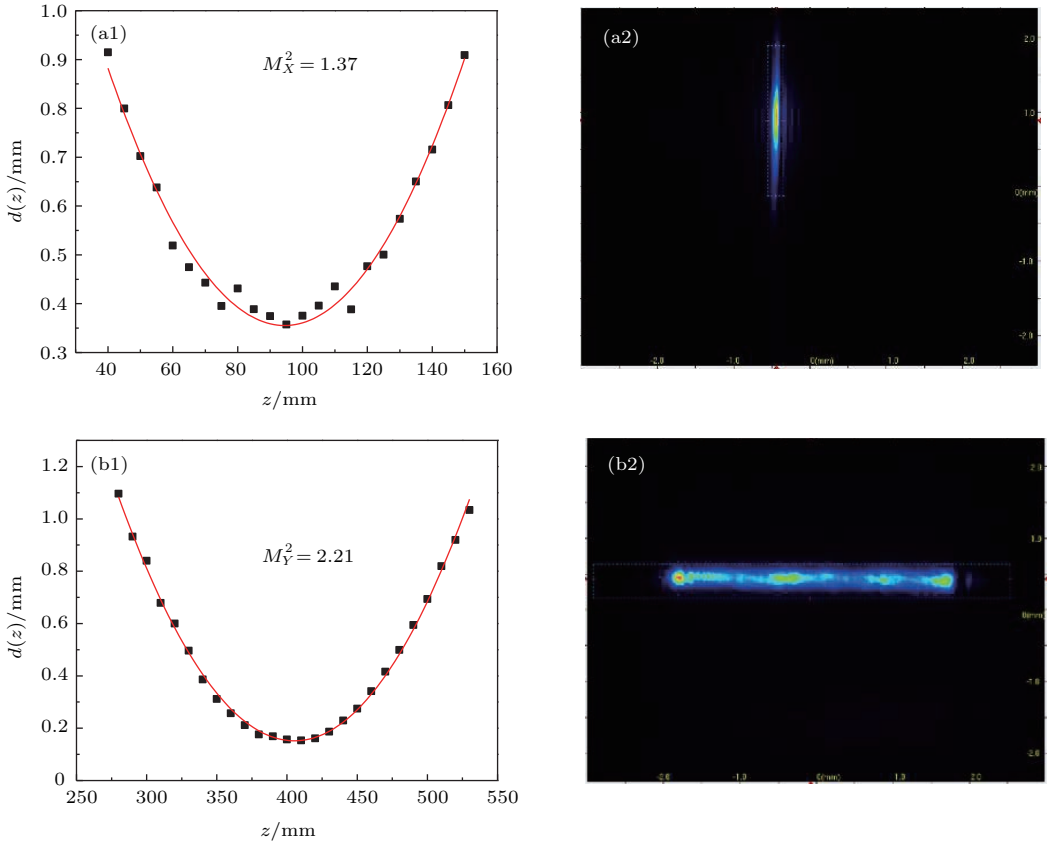


图 4 (网刊彩色) 光束质量和远场光斑图 (a) 非稳腔方向光束质量和远场光斑图; (b) 稳腔方向光束质量和远场光斑图

Fig. 4. (color online) The beam quality and far-field spot diagrams: (a) The beam quality and far-field spot diagram in the unstable direction; (b) the beam quality and far-field spot diagram in the stable direction.

采用有限元法, 利用 ANSYS 软件对 Nd:YVO_4 晶体温度分布进行数值模拟, 在抽运功率为 462 W 时, 结果如图 5 所示: 晶体的最高温度约为 367.6 K, 最大温差为 71.6 K. 在 X 方向, 温度分布几乎均匀; 在 Y 方向, 温度分布呈现中间高, 两端低的抛物线型; 在 Z 方向, 温度分布按指数线性衰减.

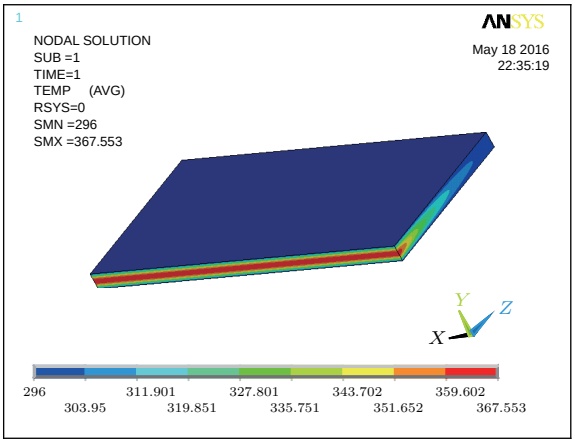


图 5 (网刊彩色) Nd:YVO4 晶体中温度分布图

Fig. 5. (color online) The Nd:YVO_4 crystal temperature distribution.

由于在水平方向上, 温度分布均匀, 无热透镜效应, 同时采用离轴共焦非稳腔, 因此, 从原则上讲, 可以通过增加板条晶体水平方向上的尺寸, 较大尺寸的晶体可以在保持抽运功率密度不变情况下, 进一步提高注入的抽运功率, 从而提高输出功率, 并且光束质量不会出现明显的下降.

4 结 论

本实验中利用 808 nm 的 LD 端面抽运 22 mm × 10 mm × 1 mm 的 Nd:YVO_4 晶体, 并采用正支混合腔结构, 最终获得最大功率为 160 W 的连续激光输出, 功率波动为 2.6%, 光-光转化效率和斜效率分别为 41.5% 和 47.7%. 在输出功率为 145 W 时, 光束质量在稳腔和非稳腔方向上分别为 2.21 和 1.37. 该实验也说明了 Innoslab 激光器的优势, 即可以通过增加板条晶体水平方向上的尺寸, 较大尺寸的晶体可以在保持抽运功率密度不变情况下, 进一步提高注入的抽运功率, 从而提高输出功率, 并且光束质量不会出现明显的下降, 这为以

后的功率提升提供了借鉴.

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160 W laser-diode end-pumped Nd:YVO_4 slab laser with positive branch hybrid resonator

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Abstract

In this paper, we present an experiment on a continuous-wave Nd:YVO_4 Innoslab laser diode-pumped at 808 nm. The LD stack is composed of six bars, with the central wavelength fixed at 808 nm by adjusting the cooling water temperature. The emission from each diode laser bar is individually collimated by micro lens, which is coupled into a coupling system. The coupling system includes a planar waveguide, four cylindrical lenses and a spherical lens. The planar waveguide is used to shape the emitting beams of LD to obtain uniform distribution. The coupling system leads to a pump power loss of $\sim$ 12%. By the coupling system, we obtain a homogeneous pumping line of $\sim$0.4 mm $\times$ 22 mm coupled into the 0.3 at. % Nd:YVO_4 (22 mm $\times$ 10 mm $\times$ 1 mm) crystal. The Nd:YVO_4 crystal is a-cut with c axis along 22 mm direction. Indium foil is used for uniform thermal contact and cooling. The laser crystal is mounted between two water-cooled copper heat sinks with two large faces 22 mm $\times$ 10 mm. The heat conduction inside the laser crystal is quasionedimensional. The two 22 mm $\times$ 1 mm surfaces are polished and antireflectioncoated for the pump light and the laser light. Temperature of LD stack and laser crystal are controlled by cooling circulating water. The resonator consists of the input mirror (M1) and the output mirror (M2). M1 is a concave mirror with a radius of $R1 = 500$ mm, which is coated for high refection (HR) at 1064 nm and high transmission (HT) at 808 nm. The output mirror (M2) is a cylindrical mirror with a radius of $R2 = -350$ mm, which is coated for HR at 1064 nm. M2 is cut and polished at one edge where the large beam exits. M1 and M2 constitute a stable resonator in vertical direction and off-axis unstable positive confocal resonator in the horizontal direction. In theory, the length of the resonator is $L = (R1 + R2)/2 = 75$ mm. In fact, the length of the resonator is the same as the theoretical value. The equivalent transmission of the resonator is $T = 1 - |R2/R1| = 30\%$. At a pumping power of 462 W, a maximum power of 160 W continuous wave laser output is obtained, with the stability being 2.6%. Considering 88% of the coupling efficiency and 95% of absorbed efficiency, the optical-to-optical efficiency and slope efficiency are 41.5% and 47.7%, respectively. When the output power is 145 W, the beam quality M^2 factors in the stable direction and unstable direction are 2.21 and 1.37, respectively. With the help of the ANSYS software, the temperature distribution in the crystal at the pumped power of 462 W is demonstrated. The temperature distributions are analogous to exponential decays in the Z-direction and parabola decay in the Y-direction, respectively. The maximum temperature difference is 71.6 K in our experiment. The thermal lens is negligible in the unstable direction because the temperature distribution is uniform. That is why the Innoslab laser is beneficial to the power scaling, as it keeps the power density constant, and enlarges the size of gain medium in the unstable direction to inject bigger power to obtain a higher power output, and maintain the constant beam quality.

Keywords: Nd:YVO_4 crystal, positive branch hybrid cavity, Innoslab

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