

## 端面泵浦渐变浓度Nd:YAG温度场数值仿真研究

阮芳芳<sup>1</sup>, 唐方颖<sup>2</sup>, 王锦红<sup>2</sup>, 吕彦飞<sup>2</sup>, 李家伟<sup>2</sup>, 王鑫欣<sup>2</sup>, 闫育辉<sup>2</sup>, 苏良碧<sup>3\*</sup>, 郑丽和<sup>2\*\*</sup><sup>1</sup>杭州医学院医学影像学院, 浙江 杭州 310053;<sup>2</sup>云南大学物理与天文学院云南省高校光电子器件工程重点实验室, 云南 昆明 650500;<sup>3</sup>中国科学院上海硅酸盐研究所人工晶体研究中心, 上海 201899

**摘要** 采用高功率半导体激光端面泵浦技术,在均一浓度Nd:YAG中心轴沿泵浦光通光方向可产生温度梯度,引起热透镜效应,降低激光输出功率与光束质量。本文结合静态热场数值仿真,建立Nd:YAG在方形平顶光泵浦条件下的热源方程,研究渐变浓度Nd:YAG在高功率激光泵浦下的温度分布。当初始泵浦功率为1000 W、泵浦脉宽时间为46  $\mu$ s、重复频率为1 kHz时,均一浓度Nd:YAG的吸收系数为5.8  $\text{cm}^{-1}$ ,其中心轴沿通光方向的温度由185  $^{\circ}\text{C}$ 逐次下降到2、4、6、8 mm处的106、51、29、26  $^{\circ}\text{C}$ ;相应地,每经过2 mm,温度下降率分别为39.5、27.5、11.0、1.5  $^{\circ}\text{C}/\text{mm}$ 。与此相对应,本文构建出一款渐变浓度Nd:YAG整体式结构,每段厚度均为1 mm,总长度为4 mm。将4段Nd:YAG的吸收系数依次调控为1.5、2.1、3.3、9.7  $\text{cm}^{-1}$ ,则沿泵浦光通光方向的中心轴温度基本维持在86.5  $^{\circ}\text{C}$ ,在渐变浓度Nd:YAG中实现沿泵浦光传输方向的温度均匀分布。

**关键词** 均一浓度Nd:YAG; 渐变浓度Nd:YAG; 数值仿真; 温度分布

中图分类号 O436

文献标志码 A

DOI: 10.3788/AOS231944

## 1 引言

高功率全固态激光器在高速切割、焊接、表面热处理、激光熔覆、激光快速成形等领域的需求日益增多<sup>[1-3]</sup>。高功率固体激光器是一类亮度增强器。激光介质在高功率受激辐射过程中,产生大量废热,造成激光介质温度升高,影响激光转换效率。与此同时,所产生的温度梯度分布,将导致介质内折射率分布不均匀,产生热应力,引起介质形变、双折射、热透镜等效应,进而影响光束质量。此外,由于光学元件局部原因造成对激光吸收率增大,导致透过型光学元件的折射率和反射型光学元件的反射方向发生变化,改变激光束腰位置,进而影响使用效果<sup>[4-6]</sup>。

为了提高激光器系统的效率和光束质量,激光器设计的关键环节之一是如何调控激光增益介质中激活稀土离子的掺杂浓度<sup>[7-10]</sup>。Wilhelm等<sup>[11]</sup>提出了一种基于纵向浓度梯度多段分布式激光介质的端面泵浦功率放大方案。Stroganova等<sup>[12]</sup>基于纵向泵浦浓度梯度型激光介质开展了热扩散模拟仿真,相较于给定长度的均一浓度激光介质,可获得更为平滑的温度曲线。在浓度梯度型激光晶体制备方面,Lebbou等<sup>[13]</sup>基于激

光后座加热技术(LHPG)制备了Yb:KY<sub>3</sub>F<sub>10</sub>晶体光纤,Yb<sup>3+</sup>浓度梯度为0~20%。Boulon等<sup>[14-15]</sup>研究了一类浓度梯度型倍半氧化物及其发光特性。

Nd:YAG具有光学均匀性好、机械性能好、物化稳定性高、热导性好等优点,是迄今为止最为重要,也是最成熟、最主流的激光材料。江海河与张庆礼团队基于自主研发的浓度梯度型Nd:YAG激光晶体,在通光方向获得相对均匀的泵浦光分布,Nd<sup>3+</sup>掺杂的原子数分数为0.39%~0.80%,在1064 nm处获得最大输出功率为24.2 W、重复频率为2 kHz、光光效率为53.8%<sup>[16]</sup>。本文基于数值仿真建立了热源方程,开展渐变浓度Nd:YAG在方形平顶光泵浦下的温度分布研究,为设计渐变浓度Nd:YAG提供了理论依据。

## 2 实验仿真

### 2.1 Nd:YAG晶体建模

借助于静态热场数值仿真,在高功率激光泵浦条件下,可直观获得激光增益介质沿泵浦光传播方向的温度数值<sup>[17-19]</sup>。图1给出了半导体激光(LD)泵浦光经过Nd:YAG的光路示意图。图1(a)代表均一浓度Nd:YAG,图1(b)代表渐变浓度Nd:YAG。

收稿日期: 2023-12-16; 修回日期: 2024-01-17; 录用日期: 2024-01-21; 网络首发日期: 2024-02-20

基金项目: 国家重点研发计划(2021YFE0104800)、国家自然科学基金(62165017, 62175209, 61925508)、云南省科技厅基础研究计划(202201AS070013, 202101AT070162, 202101BA070001-029)、云南大学创新创业项目(202310673085, S202310673191)、云南大学研究生创新项目(KC-23236050)

通信作者: \*suliangbi@mail.sic.ac.cn; \*\*zhenglihe@ynu.edu.cn

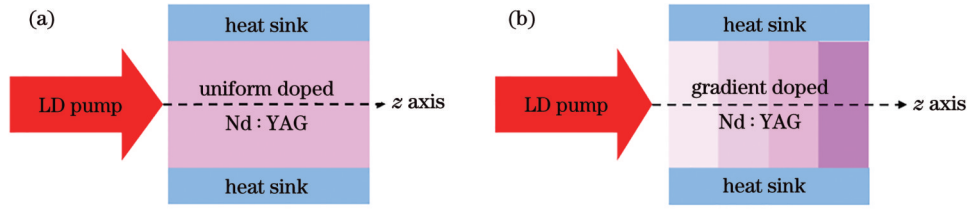


图1 LD泵浦光经过Nd:YAG的光路示意图。(a)均一浓度Nd:YAG;(b)渐变浓度Nd:YAG

Fig. 1 Schematic diagram of LD-pumped Nd:YAG with (a) uniform and (b) gradient dopants of Nd<sup>3+</sup>

Nd:YAG 通光方向为 [100], 截面为 10 mm × 10 mm。其中, 均一浓度 Nd:YAG 晶体的吸收系数为 5.8 cm<sup>-1</sup>、厚度为 8 mm, 对泵浦光的单程吸收达到 99% 以上。渐变浓度 Nd:YAG 由 4 段几何尺寸相同的 Nd:YAG 晶体组成, 每段厚度为 1 mm。通过合理设计 Nd<sup>3+</sup> 掺杂浓度和样品厚度, 在维持相同吸收率的前提下, 渐变浓度 Nd:YAG 的总长度可缩短至 4 mm。一方面, 可结合数值仿真模拟渐变浓度 Nd:YAG 与均一浓度 Nd:YAG 晶体在中心轴的温度变化; 另一方面, 相较于均一浓度 Nd:YAG 晶体, 渐变浓度 Nd:YAG 的总长度缩短, 可开展微片激光实验, 获得高光束质量、短脉冲激光输出。

## 2.2 实验仿真参数

为了方便观察中心温度场分布, 结合静态热场数值仿真, 建立端面泵浦、边缘恒温的 1/4 几何模型。泵浦光在晶体中的通光方向为  $z$  方向。设定泵浦光的束腰半径  $\omega_r$  在晶体中保持恒定, 泵浦光单程通过 Nd:YAG 激光晶体, 充分覆盖晶体增益区域以提高泵浦吸收效率。Nd:YAG 与热沉铜块接触, 通过热传导进行主动散热。表 1 给出了稳态传热数值仿真过程中 Nd:YAG 的物理参数。其中, Nd:YAG 通光截面为 10 mm × 10 mm, Nd:YAG 密度  $\rho$  为 4.56 g · cm<sup>-3</sup>, 导热系数  $\kappa$  为 14 W/(m · K), 恒压热容  $C_p$  为 590 J/(kg · K)<sup>[20]</sup>。

表 1 稳态传热数值仿真过程中 Nd:YAG 的物理参数

Table 1 Physical parameters of Nd:YAG in stable thermal numerical simulation

Parameter	Aperture $A$ /(mm × mm)	Density $\rho$ /(g · cm <sup>-3</sup> )	Thermal conductivity $\kappa$ /(W · m <sup>-1</sup> · K <sup>-1</sup> )	Heat capacity $C_p$ /(J · kg <sup>-1</sup> · K <sup>-1</sup> )
Value	10 × 10	4.56	14	590

表 2 给出了稳态传热数值仿真过程中的泵浦光参数。其中泵浦光束腰半径  $\omega_r$  为 0.5 mm, 初始泵浦光功率  $P_{in}$  为 1 kW, 泵浦光脉冲宽度  $\tau_p$  为 46  $\mu$ s, 重复频率  $f$  为 1 kHz<sup>[21]</sup>。热边界温度  $T_{cu}$  设定为 15 °C。

表 2 稳态传热数值仿真过程中的泵浦光参数

Table 2 Pump laser parameters in stable thermal numerical simulation

Parameter	$\omega_r$ /mm	$P_{in}$ /kW	$f$ /Hz	$T_{cu}$ /°C
Value	0.5	1000	1000	15

在晶体内任一点处的泵浦光强分布为  $I_i(x, y) = I_0 \exp(-\alpha \cdot l_i)$ , 式中,  $I_i(x, y)/I_0$  为泵浦光透过率,  $\alpha$  为吸收系数,  $l_i$  为泵浦光在晶体中的传输距离,  $\exp(-\alpha \cdot l_i)$  表示泵浦光经过传输距离  $l_i$  后的透过率。假设泵浦光

源为方形平顶光, 热源公式为  $Q = P_{in} \times \tau_p \times f \times \eta_h \times \alpha / (4 \times \omega_r^2) \times \exp(-\alpha_i \cdot l_i) \times S(x, y, z)$ 。采用迭代法可求解得到温度场分布。其中  $\eta_h$  为热转换系数, 即吸收的泵浦光中转化为热的份额, 由荧光量子效应和内损耗决定, 取值为 0.35<sup>[22]</sup>;  $P_{in} \times \tau_p \times f \times \eta_h$  为沉积在晶体上的功率; 分量  $\alpha / (4 \times d^2)$  为单位面积内的吸收系数;  $S(x, y, z)$  代表空间边界值。

## 3 结果与讨论

表 3 给出了 Nd:YAG 在数值仿真中的吸收系数。均一浓度掺杂的块体 Nd:YAG 的总厚度设定为 8 mm。通过合理设计 Nd<sup>3+</sup> 掺杂浓度和样品厚度, 在维持相同吸收率的前提下, 渐变浓度 Nd:YAG 的总长度可缩短至 4 mm。

表 3 稳态传热数值仿真过程中 Nd:YAG 的吸收系数

Table 3 Absorption coefficients of Nd:YAG in stable thermal numerical simulation

unit: cm<sup>-1</sup>

Symbol	(a) Gradient Nd:YAG				(b) Bulk Nd:YAG
	$\alpha_1$	$\alpha_2$	$\alpha_3$	$\alpha_4$	$\alpha_{bulk}$
Absorption coefficient	1.5	2.1	3.3	9.7	5.8

图 2 给出了在 Nd:YAG 中心轴上距离泵浦光不同位置处的温度分布, 其中图 2(a) 代表均一浓度 Nd:YAG; 图 2(b) 代表渐变浓度 Nd:YAG。初始泵浦

功率作用在均一浓度 Nd:YAG 晶体上, 通光方向  $z$  轴的温度由初始接触面的 185 °C 逐次下降到 2、4、6、8 mm 处的 106、51、29、26 °C; 与此同时, 每经过 2 mm,

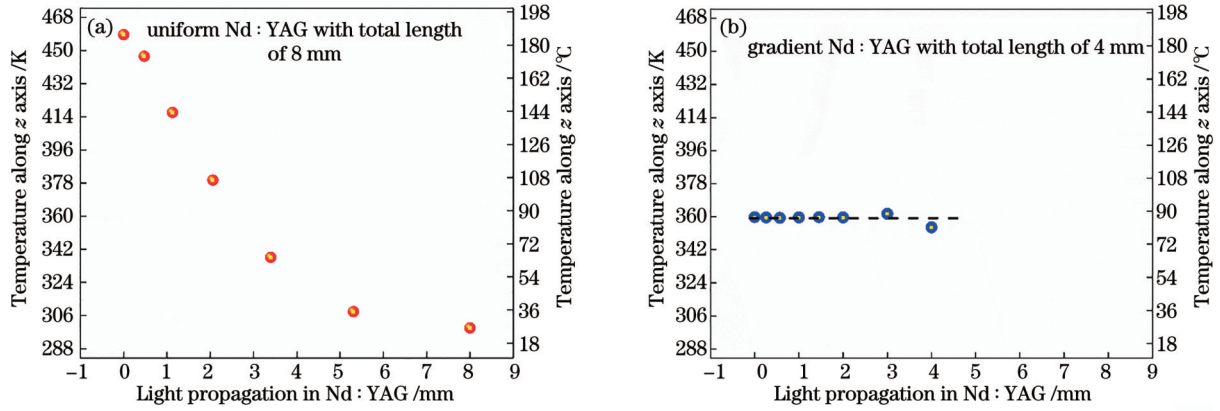


图 2 沿泵浦光传播方向 Nd:YAG 中心轴不同位置处的温度分布。(a)均一浓度 Nd:YAG;(b)渐变浓度 Nd:YAG

Fig. 2 Temperature distribution at different positions along central axis of Nd:YAG pump light propagation direction with (a) uniform and (b) gradient dopants of  $\text{Nd}^{3+}$

温度下降率分别为 39.5、27.5、11.0、1.5  $^{\circ}\text{C}/\text{mm}$ 。上述结果表明,靠近泵浦光源位置,晶体温度最高,温度梯度最大。经过多次数值仿真与优化,渐变浓度 Nd:YAG 的 4 片晶体吸收系数分别为 1.5、2.1、3.3、9.7  $\text{cm}^{-1}$ 时,可基本获得温度均匀分布;在相同泵浦条件下,最大温度为 88.5  $^{\circ}\text{C}$ ,通光方向  $z$  轴上的温度基本恒定在 86.5  $^{\circ}\text{C}$ ;最大温度与最小温度的变化幅度

为 7.5  $^{\circ}\text{C}$ 。

图 3 给出了沿 Nd:YAG 中心轴的三维可视化温度分布。温度分布一定程度上反映了增益分布,可推断渐变浓度 Nd:YAG 内部的热分布均匀性、增益分布均匀性都优于均一浓度 Nd:YAG。通过调控 Nd:YAG 的径厚比、吸收系数,可以调控增益分布与热分布均匀性。

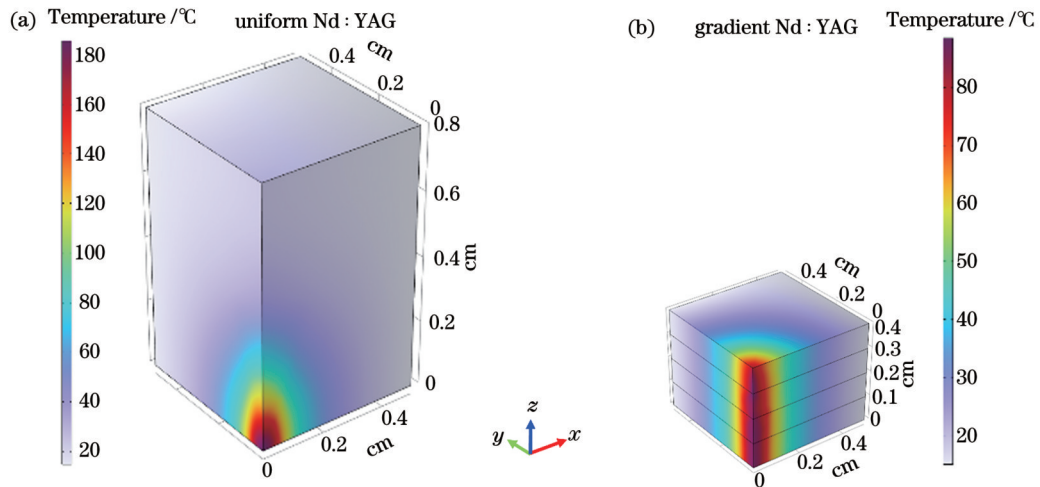


图 3 沿 Nd:YAG 中心轴的三维可视化温度分布。(a)均一浓度 Nd:YAG;(b)渐变浓度 Nd:YAG

Fig. 3 3D visualization of temperature distribution along central axis of Nd:YAG with (a) uniform and (b) gradient dopants of  $\text{Nd}^{3+}$

图 4 给出了径向温度分布情况。在均一浓度 Nd:YAG 晶体中,沿着垂直于晶体中心轴方向,自晶体中心位置向热沉方向辐射,经过 5 mm 长度,由初始位置的 185  $^{\circ}\text{C}$  下降到 15  $^{\circ}\text{C}$ ,温度下降率为 34  $^{\circ}\text{C}/\text{mm}$ 。在渐变浓度 Nd:YAG 中,自晶体中心位置向热沉方向辐射,由初始位置的 86.5  $^{\circ}\text{C}$  下降到 15  $^{\circ}\text{C}$ ,温度下降率约为 14  $^{\circ}\text{C}/\text{mm}$ 。

上述结果表明:在均一浓度 Nd:YAG 晶体中,在泵浦区域内,尤其是晶体的初始位置处,泵浦光功率很强;泵浦光经过传输距离  $l_i$  后,泵浦区域的光强将为  $P_i \exp(-\alpha \cdot l_i)$ ,即在泵浦光传输路径中,光强分布不均

匀,导致温度分布不均匀,进而产生热致双折射、热退偏和光斑分布不均匀等不良影响。在设计渐变浓度 Nd:YAG 时,合理设计每段 Nd:YAG 的吸收系数,可以使晶体内的增益场与谐振腔基模良好匹配,易得到良好的光束质量和大能量输出,同时结构简单,易实现对整体式键合晶体的主动制冷。吸收系数影响泵浦光强和热功率密度的大小,则必然影响温度场的分布。吸收系数越大,吸收效率越高,增益越大。应当综合考虑热效应和增益,选择适合的吸收系数。由此,可考虑在靠近泵浦光附近,选择  $\text{Nd}^{3+}$  低浓度掺杂的 Nd:YAG;在随后的 Nd:YAG 中, $\text{Nd}^{3+}$  掺杂浓度依



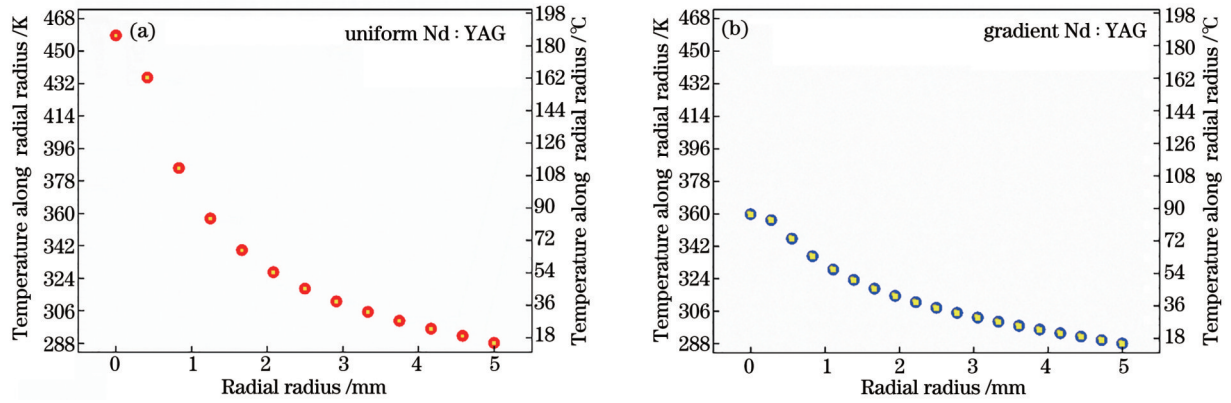


图 4 Nd:YAG 径向温度分布。(a)均一浓度 Nd:YAG;(b)渐变浓度 Nd:YAG

Fig. 4 Temperature distribution along radius direction of Nd:YAG with (a) uniform and (b) gradient dopants of Nd<sup>3+</sup>

次升高。泵浦光通过第一段 Nd:YAG, 部分光被吸收, 一方面用于产生荧光, 另一方面将产生废热; 部分透过光将继续作为第二段晶体的初始泵浦功率; 以此类推。

## 4 结 论

在初始泵浦功率为 1000 W、泵浦脉宽时间为 46  $\mu$ s、重复频率为 1 kHz 等泵浦条件下, 建立了 Nd:YAG 在端面泵浦模式下的热源方程。通过调控渐变浓度 Nd:YAG 在泵浦光通光方向上每层介质的吸收系数依次为 1.5、2.1、3.3、9.7  $\text{cm}^{-1}$ , 成功获得 Nd:YAG 沿泵浦光传输方向的温度均匀分布。上述工作为开发新型渐变浓度型键合器件提供了一类数学建模与静态热场数值仿真方法, 为研究键合器件在高功率激光泵浦下的激光输出性能提供了理论依据。

## 参 考 文 献

- [1] Li Z Y, Leng Y X, Li R X. Further development of the short-pulse petawatt laser: trends, technologies, and bottlenecks[J]. *Laser & Photonics Reviews*, 2023, 17(1): 2100705.
- [2] 侯伊育, 董海亮, 贾志刚, 等. 组分阶梯 InGaN 势垒对绿光激光二极管光电性能的影响[J]. *人工晶体学报*, 2023, 52(8): 1386-1393.  
Hou Y Y, Dong H L, Jia Z G, et al. Effect of composition step-graded InGaN barriers on photoelectric performance of green laser diode[J]. *Journal of Synthetic Crystals*, 2023, 52(8): 1386-1393.
- [3] 郭俊, 刘坚, 陈鹏, 等. Nd:CaYAlO<sub>4</sub> 单晶光纤的生长及光谱性能研究[J]. *人工晶体学报*, 2023, 52(7): 1345-1351.  
Guo J, Liu J, Chen P, et al. Growth and spectral properties of Nd:CaYAlO<sub>4</sub> single crystal fibers[J]. *Journal of Synthetic Crystals*, 2023, 52(7): 1345-1351.
- [4] 张轲, 延风平, 韩文国, 等. 高功率掺 Tm<sup>3+</sup> 光纤放大器热效应管理的泵浦方式优化理论研究[J]. *发光学报*, 2020, 41(7): 839-848.  
Zhang K, Yan F P, Han W G, et al. Theoretical study of pumping method of high power Tm<sup>3+</sup>-doped fiber amplifier for thermal effect management[J]. *Chinese Journal of Luminescence*, 2020, 41(7): 839-848.
- [5] Yang H M, Feng G Y, Zhou S H. Thermal effects in high-power Nd:YAG disk-type solid state laser[J]. *Optics & Laser Technology*, 2011, 43(6): 1006-1015.
- [6] 吴健宏, 杜仕峰, 高昀, 等. 紧凑高效型百瓦级 2  $\mu$ m 棒状 Tm:YAG 激光器[J]. *发光学报*, 2023, 44(11): 2027-2032.  
Wu J H, Du S F, Gao Y, et al. Compact and efficient hundred-watt level 2  $\mu$ m rod Tm:YAG laser[J]. *Chinese Journal of Luminescence*, 2023, 44(11): 2027-2032.
- [7] Lin Y H, Tang Z L, Zhang Z T, et al. Influence of co-doping different rare earth ions on the luminescence of CaAl<sub>2</sub>O<sub>4</sub>-based phosphors[J]. *Journal of the European Ceramic Society*, 2003, 23(1): 175-178.
- [8] Kenyon A J. Recent developments in rare-earth doped materials for optoelectronics[J]. *Progress in Quantum Electronics*, 2002, 26(4/5): 225-284.
- [9] Zheng L H, Zhao J B, Wang Y X, et al. Mid-IR optical property of Dy:CaF<sub>2</sub>-SrF<sub>2</sub> crystal fabricated by multicrystalline temperature gradient technology[J]. *Crystals*, 2021, 11(8): 907.
- [10] Dong J Y, Cui J W, Wen Y, et al. High-effective mitigation of thermal effect in multi segment and multi concentration (MSMC) Tm:YAG crystal[J]. *Infrared Physics & Technology*, 2022, 122: 104104.
- [11] Wilhelm R, Frede M, Kracht D. Power scaling of end-pumped solid-state rod lasers by longitudinal dopant concentration gradients[J]. *IEEE Journal of Quantum Electronics*, 2008, 44(3): 232-244.
- [12] Stroganova E V, Galutskiy V V, Tkachev D S, et al. Increasing pumping efficiency by using gradient-doped laser crystals[J]. *Optics and Spectroscopy*, 2014, 117(6): 984-989.
- [13] Ito M, Hraiech S, Goutaudier C, et al. Growth of Yb<sup>3+</sup>-doped KY<sub>3</sub>F<sub>10</sub> concentration gradient crystal fiber by laser-heated pedestal growth (LHPG) technique[J]. *Journal of Crystal Growth*, 2008, 310(1): 140-144.
- [14] Laversenne L, Goutaudier C, Guyot Y, et al. Growth of rare earth (RE) doped concentration gradient crystal fibers and analysis of dynamical processes of laser resonant transitions in RE-doped Y<sub>2</sub>O<sub>3</sub> (RE=Yb<sup>3+</sup>, Er<sup>3+</sup>, Ho<sup>3+</sup>) [J]. *Journal of Alloys and Compounds*, 2002, 341(1/2): 214-219.
- [15] Boulon G, Laversenne L, Goutaudier C, et al. Radiative and non-radiative energy transfers in Yb<sup>3+</sup>-doped sesquioxide and garnet laser crystals from a combinatorial approach based on gradient concentration fibers[J]. *Journal of Luminescence*, 2003, 102/103: 417-425.
- [16] Wei M E, Cheng T Q, Dou R Q, et al. Superior performance of a 2 kHz pulse Nd:YAG laser based on a gradient-doped crystal[J]. *Photonics Research*, 2021, 9(7): 1191-1196.
- [17] 王浩然, 王建磊, 李培丽, 等. 基于微通道热沉的片状激光放大器散热模拟及优化[J]. *中国激光*, 2023, 50(7): 0701002.  
Wang H R, Wang J L, Li P L, et al. Simulation and optimization of heat dissipation in slab laser amplifier based on

- microchannel heat sink[J]. Chinese Journal of Lasers, 2023, 50 (7): 0701002.
- [18] 余善恩, 杨文东, 李华军. 基于数值仿真的光学层析成像传感器结构研究[J]. 激光与光电子学进展, 2022, 59(22): 2228001. Yu S E, Yang W D, Li H J. Research on the structure of an optical tomography sensor based on numerical simulations [J]. Laser & Optoelectronics Progress, 2022, 59(22): 2228001.
- [19] Liu Y Q, Liu K Y, Li Z Y, et al. Coherently tiled Ti:sapphire laser amplification: a way to break the 10 petawatt limit on current ultraintense lasers[J]. Advanced Photonics Nexus, 2023, 2(6): 066009.
- [20] 侯立群, 祖继锋, 董玥, 等. 钕玻璃、Nd:YAG 和 Nd:GGG 热容激光特性比较[J]. 强激光与粒子束, 2006, 18(6): 881-885. Hou L Q, Zu J F, Dong Y, et al. Comparison of laser characteristics of neodymium doped glass, YAG and GGG operating in heat capacity mode[J]. High Power Laser and Particle Beams, 2006, 18(6): 881-885.
- [21] Zheng L H, Kausas A, Taira T. >MW peak power at 266 nm, low jitter kHz repetition rate from intense pumped microlaser[J]. Optics Express, 2016, 24(25): 28748-28760.
- [22] Fan T Y. Heat generation in Nd:YAG and Yb:YAG[J]. IEEE Journal of Quantum Electronics, 1993, 29(6): 1457-1459.

## Numerical Simulation of Temperature Distribution in End-Pumped Nd:YAG with Uniform and Gradient Dopants of Nd<sup>3+</sup>

Ruan Fangfang<sup>1</sup>, Tang Fangying<sup>2</sup>, Wang Jinhong<sup>2</sup>, Lü Yanfei<sup>2</sup>, Li Jiawei<sup>2</sup>, Wang Xinxin<sup>2</sup>, Yan Yuhui<sup>2</sup>, Su Liangbi<sup>3\*</sup>, Zheng Lihe<sup>2\*\*</sup>

<sup>1</sup>School of Medical Imaging, Hangzhou Medical College, Hangzhou 310053, Zhejiang, China;

<sup>2</sup>Key Laboratory of Yunnan Provincial Higher Education Institutions for Optoelectronics Device Engineering, School of Physics and Astronomy, Yunnan University, Kunming 650500, Yunnan, China;

<sup>3</sup>Artificial Crystals Research Center, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201899, China

### Abstract

**Objective** Nd:YAG with a uniform dopant of Nd<sup>3+</sup> can generate gradient temperature distribution along laser propagation under high-power semiconductor diode lasers (LDs), which may cause a thermal lens effect, and thus reduce laser output power and beam quality. Regulating the gradient dopant of Nd<sup>3+</sup> in Nd:YAG is paid great attention to for improving the efficiency and beam quality. The traditional regulation method is to fabricate Nd:YAG with gradient dopant by a unique dual-crucible technology from the Czochralski method. With the development of room temperature bonding technology, it is flexible to obtain designed gradient dopants of Nd<sup>3+</sup> with specific sample thicknesses in a monolithic structure. We propose a numerical simulation method by establishing heat source equations. The temperature distribution in Nd:YAG with uniform and gradient dopants of Nd<sup>3+</sup> under kilowatt pump power is reported accordingly. We hope that the basic strategy can help design a new gradient doped Nd:YAG monolithic gain media and understand the relationship between temperature distribution and Nd:YAG with specific dopants along laser propagation.

**Methods** Nd:YAG is employed for numerical simulation of temperature distribution along laser propagation under high pump power. The aperture of Nd:YAG is 10 mm×10 mm cut along the crystallographic axis [100]. In the case of bulk Nd:YAG with a uniform dopant of Nd<sup>3+</sup>, the absorption coefficient is set as 5.78 cm<sup>-1</sup> with a bulk length of 8 mm to ensure over 99% absorption of the pump light after single path propagation. In the case of gradient Nd:YAG, each segment has 1 mm thickness and various absorption coefficients. Meanwhile, a quarter geometric model is built to compare the temperature distribution in the central axis of bulk Nd:YAG and gradient Nd:YAG along laser propagation. The initial pump power is 1000 W and the pump pulse width time is 46 μs, with the repetition frequency of 1 kHz. The flat-top pump light is employed for temperature distribution calculation and heat source expression.

**Results and Discussions** Following the pump energy of 46 mJ at 1 kHz, the temperature distribution along laser propagation in the central axis of bulk Nd:YAG decreases from 185 to 26 °C. The temperature is reduced to 106, 51, and 29 °C at the positions of 2, 4, and 6 mm in bulk Nd:YAG, respectively. This indicates that the temperature close to the pump light is the highest in a bulk Nd:YAG. By adjusting the absorption coefficient to 1.5, 2.1, 3.3, and 9.7 cm<sup>-1</sup> for each segment with 1 mm thickness in gradient Nd:YAG, the constant distribution of temperature around 86.5 °C is obtained. The maximum temperature is 88.5 °C when the temperature difference between maximum and minimum value is 7.5 °C. Additionally, by properly designing the sample thickness and absorption coefficient of the gradient Nd:YAG, the

total thickness can be shortened to 4 mm, which is beneficial for ultrashort pulse generation in microcavity.

The temperature decrease rate in bulk Nd:YAG is 34 °C/mm along the radial direction from the central axis of Nd:YAG to the thermal sink copper. In the case of gradient Nd:YAG, the temperature decreasing rate is around 14 °C/mm.

**Conclusions** A numerical simulation method by establishing heat source equations is proposed for temperature distribution evaluation in bulk Nd:YAG and gradient Nd:YAG. The temperature distribution in gradient Nd:YAG shows a constant distribution of temperature around 86.5 °C under pump energy of 46 mJ at a repetition rate of 1 kHz. This confirms that the design of monolithic gain media such as gradient Nd:YAG can help understand the temperature distribution along the central axis of Nd:YAG along laser propagation.

**Key words** uniform Nd:YAG; gradient Nd:YAG; numerical simulation; temperature distribution