第 50 卷 第 7 期/2023 年 4 月/中国激光 研究论文

中国激光

# 3 μm 高效率 Er∶YAG 循环级联脉冲激光器

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**摘要** 报道了室温下基于循环级联的高效率Er∶YAG中红外脉冲激光器，采用循环级联谐振腔，通过优化晶体长度提高光束交叠效率，获得高效率中红外激光输出。实验中使用两种掺杂浓度（原子数分数分别为25%和10%）的长度为2 mm Er∶YAG晶体作为增益介质，测得波长为2937 nm的中红外激光的输出斜效率分别为37.2%和36.5%，均突破了33.2%的Stokes极限。据我们所知，这是首次在室温下使用较低掺杂浓度（原子数分数为10%）的Er∶YAG晶体获得了超过Stokes极限的高效率3 μm中红外激光输出。

**关键词** 激光器；$Er^{3+}$激光器；循环级联；中红外激光器；高效率

**中图分类号** TN248.1 **文献标志码** A **DOI：** 10.3788/CJL220992

## 1 引 言

近年来，中红外（MIR）激光器因具有独特优势而引起了人们的广泛关注。例如3 μm波段处于水分子的强吸收带内[1]，可应用于医疗外科手术、微量气体检测、遥感及红外对抗[2-3]。此外，3 μm波段激光器也是$Fe^{2+}$∶ZnSe晶体或中红外光参量振荡器（OPO）的良好泵浦源，可以实现3～15 μm的中远红外激光输出[4-5]。使用掺杂$Dy^{3+}$、$Ho^{3+}$或$Er^{3+}$的激光增益介质可获得3 μm附近的中红外激光。其中，由于缺乏合适的泵浦源，掺$Dy^{3+}$、$Ho^{3+}$中红外激光器的发展尚不成熟[6-7]。相比之下，掺$Er^{3+}$激光晶体在970 nm附近有一个较强的吸收带，因此可使用高功率InGaAs半导体二极管进行泵浦。但是，在绝大部分掺铒增益基质中，$^4I_{13/2}$中红外下能级的寿命（2.5～10.0 ms）比$^4I_{11/2}$上能级的寿命（0.1～1.5 ms）更长[8]，难以实现粒子数反转，有严重的自终止效应[9]，从而阻碍了激光振荡。为了解决这一问题，通常需要较高的$Er^{3+}$掺杂浓度（原子数分数为30%～50%），通过能量传递上转换过程（ETU）来减少中红外激光下能级粒子数，从而实现粒子数反转[10]，而热效应则会随掺杂浓度的提高而愈发严重，进而限制了平均输出功率的进一步提高。级联$^4I_{13/2}$→$^4I_{15/2}$近红外（NIR）激光振荡同样可起到减少$^4I_{13/2}$中红外激光下能级粒子数的作用，从而在较低的掺杂浓度下实现3 μm激光输出[11-12]，但其转换效率较低，获得的中红外激光输出效率也并不高。我们最近的工作证明了室温下较低掺杂浓度Er∶YAG晶体中循环级联过程的存在[13]，该过程能够实现粒子数循环，具有提高转换效率的潜力。然而，在我们之前的实验中，最大斜效率未超过10%[14]。在循环级联的基础上进一步提高斜效率是一个有意义的探索。

本文分析了Er∶YAG晶体中红外激光输出斜效率的两个主要影响因素，即量子效率和交叠效率。分析了循环级联提高量子效率的作用机理，采用循环级联谐振腔，通过减小晶体长度提高了泵浦模式和激光模式的交叠效率。在两种掺杂浓度（原子数分数分别为10%和25%）的长度为2 mm的Er∶YAG晶体中获得了2.94 μm中红外激光，输出斜效率分别为36.5%和37.2%，突破了Stokes极限。

## 2 斜效率影响因素分析

### 2.1 量子效率

激光斜效率的影响因素之一为量子效率，量子效率与发射的激光光子数和泵浦光子数的比有关，激光光子数与泵浦光子数之比越高，量子效率也就越高。在我们之前的工作中，发现了Er∶YAG晶体中的循环级联过程[13]，研究结果显示Er∶YAG的近红外级联发射和激发态吸收（ESA）的特征波长分别为1469 nm和1676 nm。根据图1所示的Er∶YAG晶体的相关能级结构，循环级联的物理过程可描述为：两个处于基态的$Er^{3+}$离子吸收两个976 nm泵浦光子跃迁至$^4I_{11/2}$中红外

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**收稿日期：** 2022-06-23；**修回日期：** 2022-07-26；**录用日期：** 2022-08-10；**网络首发日期：** 2022-08-20

**基金项目：** 国家自然科学基金（62075003，62275007）、北京市自然科学基金（4202007，KZ202110005010）

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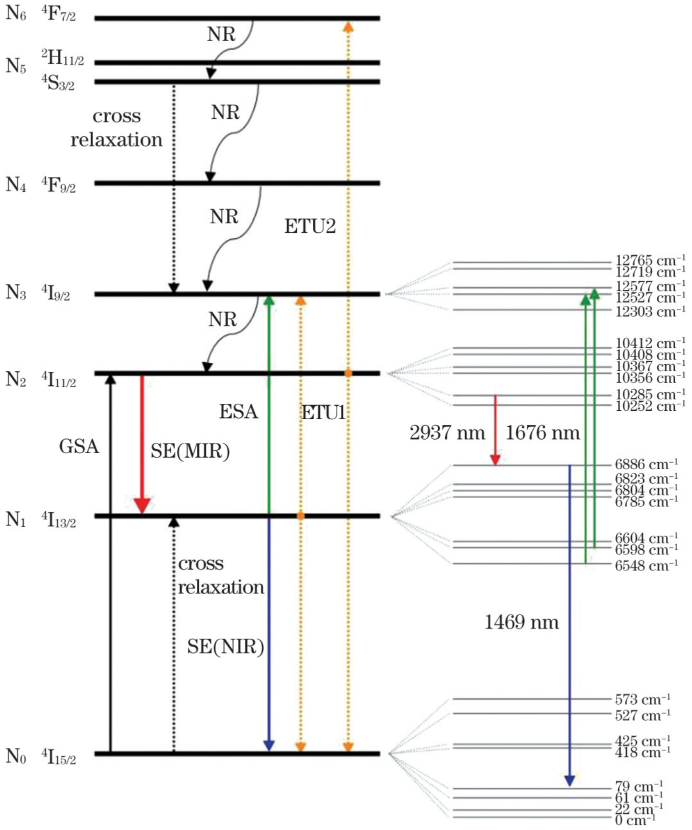


图 1　Er：YAG 部分能级结构示意图

Fig. 1　Schematic of partial energy levels of Er：YAG

上能级[即基态吸收(GSA)过程]，随后通过受激发射(SE)填充$^4I_{13/2}$能级，并辐射两个 2940 nm 光子。这两个处于$^4I_{13/2}$能级的$Er^{3+}$，其中一个返回基态并辐射 1469 nm 光子，该光子通过与基质声子发生非弹性碰撞，将部分能量传递给声子，自身转化为特征波长为 1676 nm 的可参与激发态吸收的光子，另一个$^4I_{13/2}$能级中的$Er^{3+}$吸收这一光子的能量跃迁至$^4I_{9/2}$能级，并通过快速无辐射跃迁(NR)返回至$^4I_{11/2}$中红外上能级，再通过受激发射向下跃迁，从而产生第三个 2940 nm 光子。根据上述分析，这一过程吸收两个泵浦光子，发射三个激光光子，实现了 1.5 倍的量子效率，提高了中红外激光的输出斜效率。

### 2.2　交叠效率

除了量子效率，激光斜效率($\eta$)也与交叠效率($\eta_B$)成正比。交叠效率是指谐振腔模与激光介质的泵浦功率或增益分布之间的空间交叠，可以用泵浦模与谐振腔内激光模之间交叠的积分来定义两光束的交叠效率[15]：

$$\eta_B=\frac{\int g_r(r)I_B(r)2\pi r\mathrm{d}r}{\int g_r^2(r)2\pi r\mathrm{d}r}, \tag{1}$$

式中：$g_r$为增益分布；$I_B$为光束分布；$r$为光斑半径。假设光斑均呈高斯分布，泵浦光和激光的光斑尺寸分别为$\omega_g$和$\omega_B$，则

$$\begin{cases} g_r(r)=\exp\left(-2r^2/\omega_g^2\right) \\ I_B(r)=\exp\left(-2r^2/\omega_B^2\right) \end{cases}。 \tag{2}$$

经计算，光束的交叠效率可表示为

$$\eta_B=\frac{2\omega_B^2}{\omega_B^2+\omega_g^2}。 \tag{3}$$

根据式(3)，在$\omega_B$一定的情况下，通过适当减小泵浦光的光斑大小$\omega_g$可以提高交叠效率$\eta_B$。为了验证上述分析，我们分别模拟和实测了泵浦光经过耦合系统后的分布情况，泵浦源为 976 nm 稳波长光纤耦合输出的激光二极管(LD)，其中心波长为 976 nm，芯径为 106.5 μm，数值孔径为 0.22。图 2 为泵浦光经过整形系统的 Zemax 光线追迹示意图，F1 和 F2 分别为两个焦距为 50 mm 的平凸球面透镜。根据模拟结果，泵浦光经过整形后的束腰直径约为 240 μm，发散角约为 13°。图 3 为使用刀口法实际测量的泵浦光通过整形系统后的分布情况，聚焦后的泵浦光束腰直径约为 200 μm，发散角约为 14°，与模拟结果基本吻合。

根据模拟和实测结果可估算，在 10 mm 左右的传播距离内，泵浦光直径将由束腰处的 0.2 mm 增大至约 3.0 mm。此外，我们也模拟了使用不同晶体长度后激光的模场分布，结果显示激光模场的分布相似，其变化对交叠效率的影响很小，在这种情况下，交叠效率主要受泵浦光平均光斑尺寸的影响。对于较长的增益介质，泵浦光在晶体内不同位置处的光斑大小差异很大，

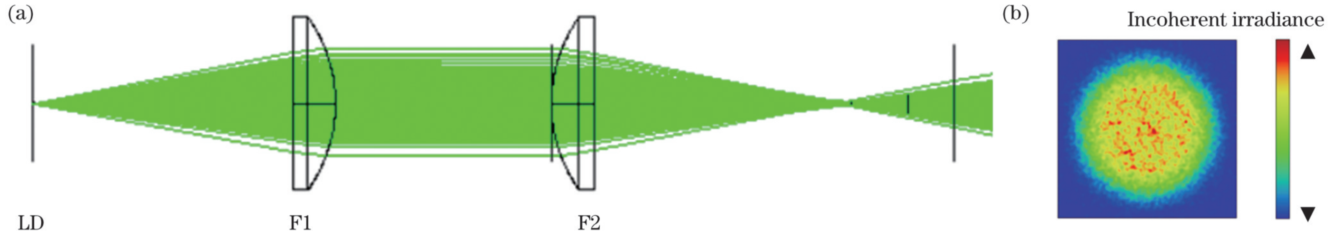
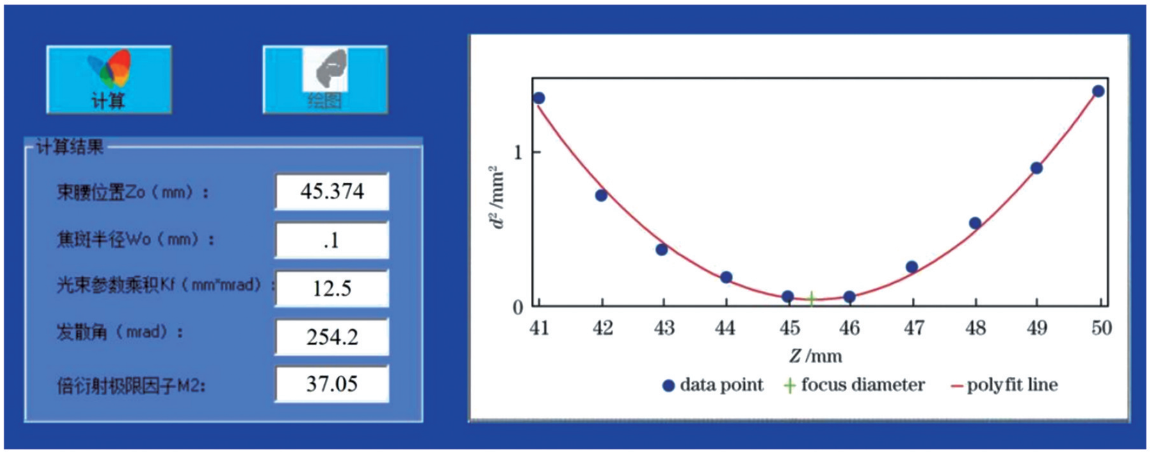


图 2 泵浦光经过整形系统后的模拟结果。(a)Zemax 光线追迹示意图;(b)束腰处光的泵浦分布

Fig. 2 Simulation results of pump light after passing shaping system. (a) Schematic of Zemax light tracing; (b) pump light distribution at beam waist



计算结果

束腰位置Zo（mm）： 45.374

焦斑半径Wo（mm）： .1

光束参数乘积Kf（mm*mrad）： 12.5

发散角（mrad）： 254.2

倍衍射极限因子M2: 37.05

图 3 刀口法实测泵浦光分布

Fig. 3 Pump light distribution measured by knife method

使得泵浦光束在晶体有效吸收长度内的平均半径增大,这就造成了腔内泵浦光模场与激光模场的匹配度较差,光束之间的交叠效率很低,在晶体后部很长的一段距离内,有相当比例的泵浦光虽然被晶体吸收,但未能转化为激光输出能量,使得激光输出的斜效率降低。因此,减小增益介质长度有助于优化泵浦光模场与激光模场的匹配,提高交叠效率。

根据上述分析可知,利用 Er∶YAG 晶体中的循环级联过程,在高量子效率的基础上,通过优化晶体长度提高交叠效率有望提升中红外激光斜效率。

## 3 实验装置

实验装置如图 4 所示,根据循环级联过程中的相关特征波长[13],专门设计了谐振腔腔镜的镀膜参数,后腔镜(RM)镀有 976 nm 泵浦光的增透射介质膜及对 1469 nm 近红外波段和 2937 nm 中红外波段高反射的介质膜;输出耦合镜(OC)镀有对 1469 nm 近红外波段高反射且对 2940 nm 中红外波段的透过率为 2.5% 的介质膜。在这样的谐振腔中,1469 nm 和 2937 nm 均可实现激光振荡,从而实现了近红外波段和中红外波段的级联。实验中使用了 4 种掺杂浓度(原子数分数分别为 7.5%、10%、15%、25%)的 Er∶YAG 晶体,并沿其〈111〉晶向进行切割,横截面大小均为 3 mm×3 mm,Er 原子数分数分别为 7.5%、10%、15% 的 Er∶YAG 晶体长度($l$)为 10 mm 和 2 mm,Er 原子数分数为 25% 的 Er∶YAG 晶体长度为 5 mm 和 2 mm,两晶体端面被抛光,没有镀膜。抽运光经过两个平凸球面透镜组成的耦合系统,聚焦到激光晶体中进行端面泵浦,实际

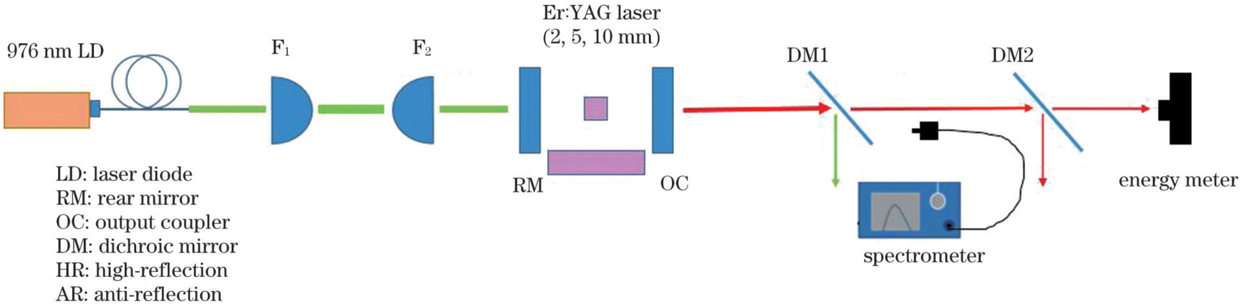


图 4 室温 Er∶YAG 循环级联激光器实验装置示意图

Fig. 4 Schematic of experimental devices for cyclic Er∶YAG laser at room temperature

测量聚焦后的泵浦光腰半径约为 100 μm。图 4 中二向色镜 1(DM1)为对 976 nm 具有高反射率且对 1400～1800 nm 和 2700～3000 nm 增透射的双色镜，用于反射未被晶体吸收的抽运光；二向色镜 2(DM2)为对 1400～1800 nm 具有高反射率且对 2700～3000 nm 增透射的双色镜，用于反射近红外激光，精确测量中红外激光输出。为减小 Er∶YAG 晶体内的热积累，实验时泵浦源设置为脉冲模式，脉冲宽度为 9.5 ms，此脉宽对应 $^4I_{13/2}$的能级寿命[16]，重复频率设为 1 Hz。

## 4 实验结果与讨论

### 4.1 激光输出光谱

为了确认激光器在级联状态下工作，我们首先在未加入 DM2 的情况下，使用光谱仪测量了 4 种掺杂浓度晶体的输出光谱图，结果如图 5 所示，其中 λ 为波长。

在 4 种掺杂浓度晶体的输出光谱中，均能观察到近红外 1469 nm 和中红外 2937 nm 两个发射峰。根据 Er∶YAG 晶体能级波数可确定发射波长与能级跃迁的对应关系。其中，近红外 1469 nm 对应于 $^4I_{13/2}$的第 7 斯塔克能级和 $^4I_{15/2}$的第 4 斯塔克能级之间的跃迁辐射，中红外 2937 nm 对应于 $^4I_{11/2}$的第 2 斯塔克能级与 $^4I_{13/2}$的第 7 斯塔克能级之间的跃迁辐射；$^4I_{13/2}$能级粒子通过激发态吸收过程跃迁至 $^4I_{9/2}$能级，再通过快速无辐射跃迁返回 $^4I_{11/2}$中红外上能级参与 2937 nm 激光发射[13]。上述结果表明实验中近红外与中红外已在谐振腔内形成级联振荡。

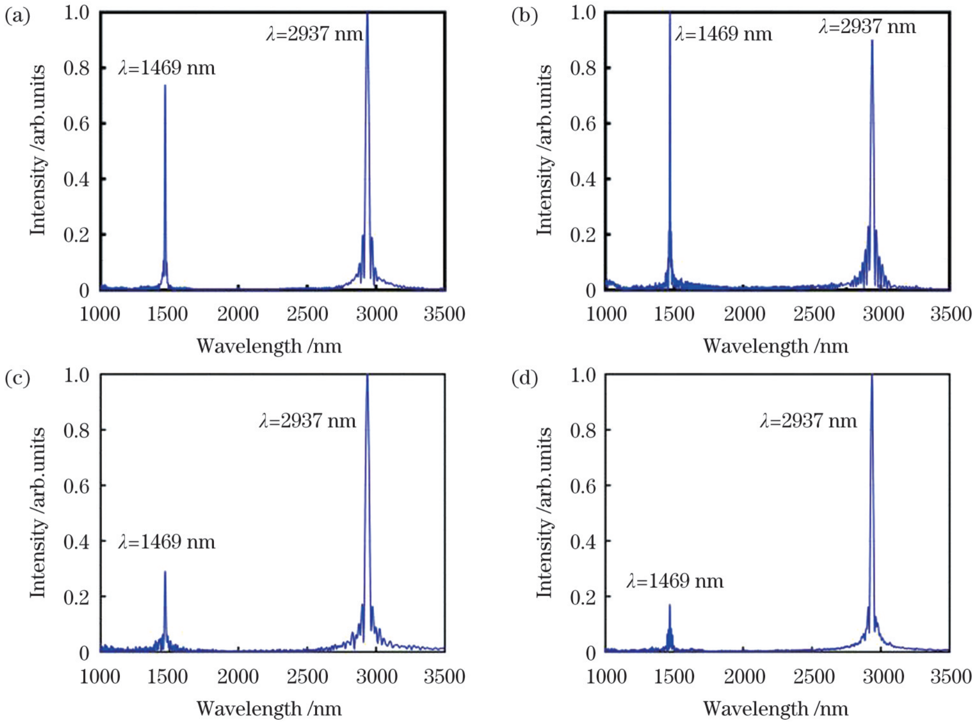


图 5 室温 Er∶YAG 级联激光器发射谱。(a)Er 的原子数分数为 7.5%；(b)Er 的原子数分数为 10%；(c)Er 的原子数分数为 15%；(d)Er 的原子数分数为 25%

Fig. 5 Emission spectra of cyclic Er∶YAG lasers at room temperature. (a) Er atomic fraction is 7.5%; (b) Er atomic fraction is 10%; (c) Er atomic fraction is 15%; (d) Er atomic fraction is 25%

### 4.2 激光输出效率

在循环级联的基础上，为了探究 Er∶YAG 晶体长度对中红外激光输出特性的影响，我们在光路中加入 DM2，测量 4 种掺杂浓度不同长度晶体的输出能量-泵浦吸收能量曲线，结果如图 6 所示。表 1 汇总了不同晶体下实验测得的起振阈值和激光输出斜效率。

如表 1 实验数据所示，对于晶体长度为 10 mm 和 5 mm 的各掺杂浓度 Er∶YAG 晶体，其起振阈值均大于 23 mJ，而对于晶体长度为 2 mm 的 Er∶YAG 晶体，起振阈值均低于 17 mJ，晶体长度较大的 Er∶YAG 的起振阈值整体高于 2 mm 的 Er∶YAG 晶体。在 2937 nm 中红外激光输出斜效率方面，在相同掺杂浓度下，2 mm 晶体所测得的激光输出斜效率与较长的激光晶体相比均有大幅提高。值得注意的是，对于 Er 原子数分数为 10% 的 Er∶YAG 晶体：晶体长度为 10 mm 时，中红外激光起振阈值为 23.4 mJ，斜效率为 23.5%；晶体长度为 2 mm 时，中红外激光起振阈值为 11.4 mJ，斜效率为 36.5%，相较于 10 mm 长的晶体，阈值降低了 51.3%，斜效率提高了 55.3%。据我们所知，这是首次在室温较低掺杂 Er∶YAG 晶体中获得了超过 Stokes 极限的输出斜效率。

上述实验结果表明，当缩短晶体长度后，激光起振阈值大幅降低，对于 4 种掺杂浓度的晶体，中红外激光的斜效率均有显著提高。实验结果证明了优化泵浦光与激光的交叠效率有助于中红外激光输出性能的提升。在实验中通过使用循环级联腔及优化交叠效率，

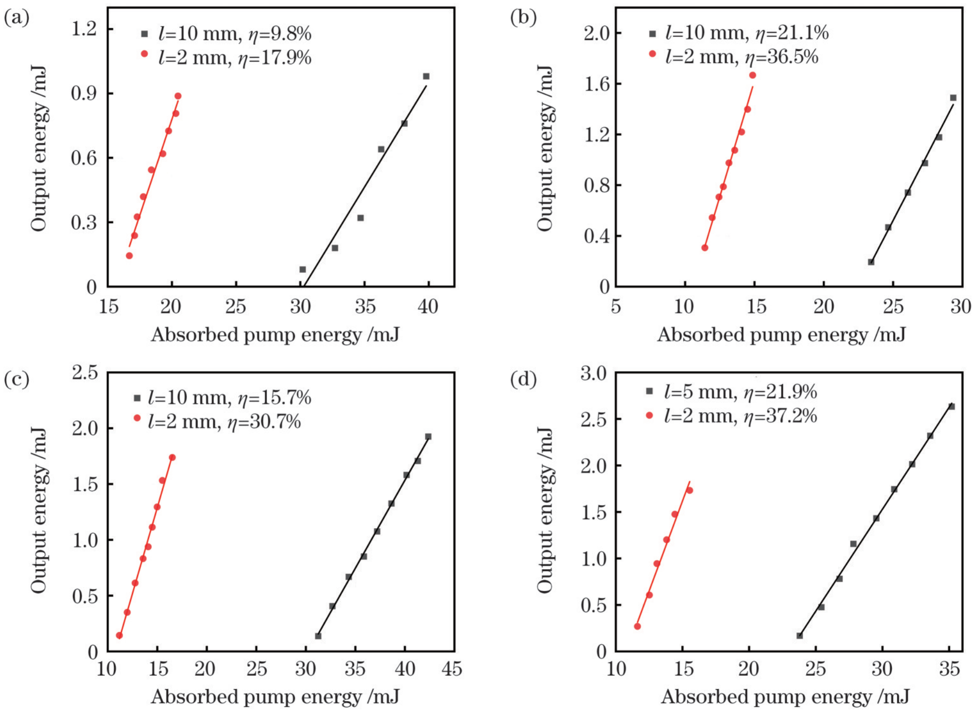


图 6　2937 nm 激光输出能量随吸收泵浦能量的变化。(a)Er 原子数分数为 7.5%；(b)Er 原子数分数为 10%；(c)Er 原子数分数为 15%；(d)Er 原子数分数为 25%

Fig. 6　Measured output energy of 2937 nm laser versus absorbed pump energy. (a) Er atomic fraction is 7.5%; (b) Er atomic fraction is 10%; (c) Er atomic fraction is 15%; (d) Er atomic fraction is 25%

表 1　各掺杂浓度下不同晶体长度 Er∶YAG 晶体的实验数据

Table 1　Experimental data of Er∶YAG crystals with different crystal lengths for each doping concentration

| Parameter | Atomic fraction is 7.5% | | Atomic fraction is 10% | | Atomic fraction is 15% | | Atomic fraction is 25% | |
|---|---|---|---|---|---|---|---|---|
| | Crystal length of 10 mm | Crystal length of 2 mm | Crystal length of 10 mm | Crystal length of 2 mm | Crystal length of 10 mm | Crystal length of 2 mm | Crystal length of 5 mm | Crystal length of 2 mm |
| Threshold /mJ | 30.1 | 16.6 | 23.4 | 11.4 | 31.2 | 11.2 | 23.8 | 11.6 |
| Slope efficiency /% | 9.6 | 17.9 | 23.5 | 36.5 | 15.7 | 30.7 | 21.9 | 37.2 |

获得了波长为 2937 nm，超过 Stokes 极限的激光输出斜效率。

## 5　结　论

在循环级联的基础上，利用优化的循环级联腔，探究了通过优化晶体长度提高光束交叠程度对中红外激光输出斜效率的影响，实现了 3 μm 高效率 Er∶YAG 循环级联激光器。实验结果显示，适当缩短晶体长度后，中红外激光的起振阈值大幅降低，输出斜效率获得显著提高。值得一提的是，在室温下使用长度为 2 mm 的 Er 原子数分数为 10% 和 25% 的 Er∶YAG 作为增益介质，分别获得了 36.5% 和 37.2% 的中红外激光输出斜效率，突破了 Stokes 极限。据我们所知，这也是首次在室温下使用较低掺杂浓度(Er 原子数分数为 10%)的 Er∶YAG 级联激光器实现了 3 μm 中红外激光的高效率输出，并且 Er 原子数分数为 10% 的 Er∶YAG 相比于 Er 原子数分数为 25% 的 Er∶YAG 能够带来更小的热效应，有望获得更高的平均输出功率。这项工作有助于推动 3 μm 中红外高效率高平均功率激光器的发展。

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# 3-μm High-Efficiency Er∶YAG Cyclic Cascade Pulse Laser

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## Abstract

**Objective** Mid-infrared lasers at approximately 3 μm can be used in many fields such as medical surgery, trace gas detection, remote sensing, and infrared countermeasures. Such laser source can be obtained via Dy$^{3+}$-, Ho$^{3+}$-, or Er$^{3+}$-doped laser active medium. The development of Dy$^{3+}$- and Ho$^{3+}$-doped lasers is limited because of the lack of a suitable pump source. In contrast, there is a strong absorption band of Er$^{3+}$-doped crystals at approximately 970 nm and they can be pumped by well-developed high-power InGaAs LDs. However, the transition of Er$^{3+}$ ions at approximately 3 μm wavelength is self-terminating because the lifetime of the initial laser level is considerably shorter than that of the terminal laser level. To overcome this “bottleneck”, Er$^{3+}$ ions with a high atomic fraction of 30%–50 % are typically required to depopulate lower laser level $^4I_{13/2}$. The thermal effects increase with increasing doping concentration. Cascading $^4I_{13/2}\rightarrow{}^4I_{15/2}$ near-infrared laser emission can achieve a 3-μm-laser output at an extremely low doping concentration but at the expense of reducing the conversion efficiency. In our recent study, it has been proven that the cyclic cascade can improve the efficiency of a 3-μm-laser in Er∶YAG crystals, with a low doping concentration at room temperature. However, the maximum slope efficiency does not exceed 10%. On the basis of the cyclic cascade, improving the slope efficiency is a meaningful attempt.

**Methods** In this study, we theoretically analyzed the two main factors influencing the mid-infrared (MIR) laser slope efficiency in Er∶YAG crystals, namely, quantum efficiency and overlapping efficiency. We analyzed the mechanism of improving the quantum efficiency by a cyclic cascade. For the overlapping efficiency, we simulated the distributions of the pump light and laser mode field and analyzed their influence on the overlapping efficiency. Next, the coating parameters of the cavity mirror were designed according to the relevant characteristic wavelengths in the cyclic cascade process. Er∶YAG crystals with doping concentrations (atomic fractions) of 7.5%, 10%, 15%, and 25% were used in the experiment and cut along their 〈111〉 crystal direction, with cross-sections of 3 mm×3 mm. The lengths of the Er∶YAG crystals with atomic fractions of 7.5%, 10%, and 15% were 10 mm and 2 mm, and the lengths of Er∶YAG crystals with atomic fraction of 25% were 5 mm and 2 mm. The pumping source was a stable wavelength fiber-coupled laser diode with a central emission wavelength of 976 nm. A spectrometer was used to measure the laser output spectrum and determine whether a cascade oscillation was formed. An energy meter was used to measure the output energy and other related parameters. Then, the laser output slope efficiency was calculated to analyze the influence of improving the overlapping efficiency by optimizing the crystal length on the slope efficiency.

**Results and Discussions** In the output spectra of the crystals with four doping concentrations, two emission peaks in near-infrared (1469 nm) and mid-infrared (2937 nm) bands can be observed (Fig. 5), showing that the near-infrared light and mid-infrared light have formed a cascade oscillation in the cavity. For Er∶YAG crystals with lengths of 10 mm and 5 mm, the threshold is greater than 23 mJ, whereas for Er∶YAG crystals with a length of 2 mm, the threshold is lower than 17 mJ. The threshold of Er∶YAG crystals with a larger length is generally higher than 2 mm (Fig. 6 and Table 1). In terms of the 2937-nm mid-infrared laser output slope efficiency, under the same doping concentration, the laser slope efficiency of the 2-mm long crystal is significantly improved compared with that of the longer laser crystal. In particular, for Er∶YAG crystals with an atomic fraction of 10%, when the crystal length is 10 mm, the mid-infrared laser threshold is 23.4 mJ, and the slope efficiency is 23.5%; when the crystal length is 2 mm, the mid-infrared laser threshold is 11.4 mJ, and the slope efficiency is 36.5%. Compared with the 10-mm long crystal, the threshold is reduced by 51.3%, and the slope efficiency is increased by 55.3%. To the best of our knowledge, this is the first time that a slope efficiency exceeding the Stokes limit has been obtained for low-doped Er∶YAG crystals at room temperature (Fig. 6 and Table 1).

**Conclusions** A high-efficiency cyclic cascade Er∶YAG mid-infrared pulsed laser at room temperature is reported. Based on the cyclic cascade, using the optimized cyclic cascade cavity, the influence of optimizing the crystal length to improve the beam overlap on the slope efficiency of the mid-infrared laser is explored. The experimental results show that by appropriately shortening the crystal length, the threshold of mid-infrared laser oscillation is reduced considerably, and the slope efficiency is significantly improved. Slope efficiencies of 2937 nm mid-infrared lasers up to 36.5% and 37.2%, exceeding the Stokes limit of 33.2%, are achieved in Er∶YAG crystals with a length of 2 mm and Er atomic fractions of 25% and 10%, respectively. To the best of our knowledge, this is the first time that an Er∶YAG crystal with a low doping concentration (atomic fraction of 10%) is used for a high-efficiency 3-μm mid-infrared laser output exceeding the Stokes limit at room temperature. Moreover, Er∶YAG crystals with an Er atomic fraction of 10% can produce less thermal effect than Er∶YAG crystals with an Er atomic fraction of 25% and is expected to obtain a higher average output power. This study can help to promote the development of 3-μm mid-infrared high efficiency high average power lasers.

**Key words** lasers; $Er^{3+}$ lasers; cyclic cascade; mid-infrared laser; high efficiency