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# 基于零声子线泵浦的高效率Yb:YAG薄片激光器

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**摘　要：**高功率激光器在工业应用领域的需求不断增长，提高光-光转化效率是降低其生产制造成本的关键途径。针对提高激光器光-光转化效率所面临的增益介质的热负荷问题，利用锁定波长的969 nm“零声子线”泵浦、自主研制的高性能Yb:YAG薄片晶体和48冲程泵浦系统等，搭建了高效的连续Yb:YAG薄片激光器系统，实现了最高输出功率373 W，光-光转化效率可达73.37%。其优异性能为后续开展千瓦级超快Yb:YAG薄片激光器研究奠定了基础。

**关键词：**薄片激光器；多冲程泵浦；Yb:YAG；高效率
**中图分类号：**TN248　　**文献标识码：**A　　**doi：**10.3788/gzxb20245302.0214002

## 0　引言

近年来，高功率激光器发展迅速，在焊接、切割和熔覆等工业应用领域的需求不断增长[1-5]。传统棒状激光器在高功率运转过程中，存在严重的热透镜和热畸变等效应，极大地限制了激光器输出功率的提升，同时降低了激光的光束质量[6]。面对这一问题，人们对增益介质的结构进行不断改进和优化，发展出诸如光纤[7]、板条[8]以及薄片[9]等增益介质结构。光纤激光器通过增大增益介质表面积和体积的比值将光纤内的热积累进行有效扩散，并且具有很高的单程增益，通过光纤结构的波导效应可以获得高光束质量的激光。然而，光纤激光器在高功率下仍面临自相位调制和受激拉曼散射等非线性效应带来的挑战。板条激光器采用侧向面泵浦结构，其温度梯度发生在板条晶体厚度方向上，光传播方向近似与温度梯度方向平行，可有效减缓晶体热效应。然而其他方向的热畸变仍然存在，并且激光输出发散角较大，技术也较为复杂[10, 11]。薄片激光器（Thin Disk Lasers, TDLs）是将增益介质做成极薄的圆盘状晶体结构（直径约10～25 mm，厚度约100～300 μm）[12, 13]，这种独特的几何结构显著提高了晶体的散热效率，使其在工作过程中仅存在一维的轴向热梯度，降低了晶体的热透镜、热畸变等效应，可以有效提升输出激光的光束质量。薄片激光器因具有功率可扩展、冷却效率高、波前畸变小等优点，成为下一代高功率、高能量、高峰值功率激光器的理想方案之一[12]。

薄片晶体轴向尺寸小，泵浦光单次通过厚度小于300 μm的薄片时吸收率低，影响激光器的光-光转化效率。增加泵浦光通过晶体的次数来提高薄片晶体的吸收效率[14]，是提高激光器转化效率的一种有效手段。1994年，德国斯图加特GIESEN A教授等[9]首次提出薄片激光器概念，展示了薄片晶体在高功率、高转化效

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率和高光束质量激光器极大的应用潜力。随后，该课题组报道了8冲程泵浦结构的薄片激光器，平均功率为13.5 W，光-光转化效率达到50%[12]。近年来，研究人员把泵浦次数从8次增加到了44次，转化效率提升至63%[15-17]。2015年，SCHUHMANN K等设计出了多种泵浦结构，最多可实现108次泵浦[14]。2021年，德国通快公司采用72冲程泵浦结构，从单个薄片获得了12 kW的平均功率和73%的光-光转化效率[18]。

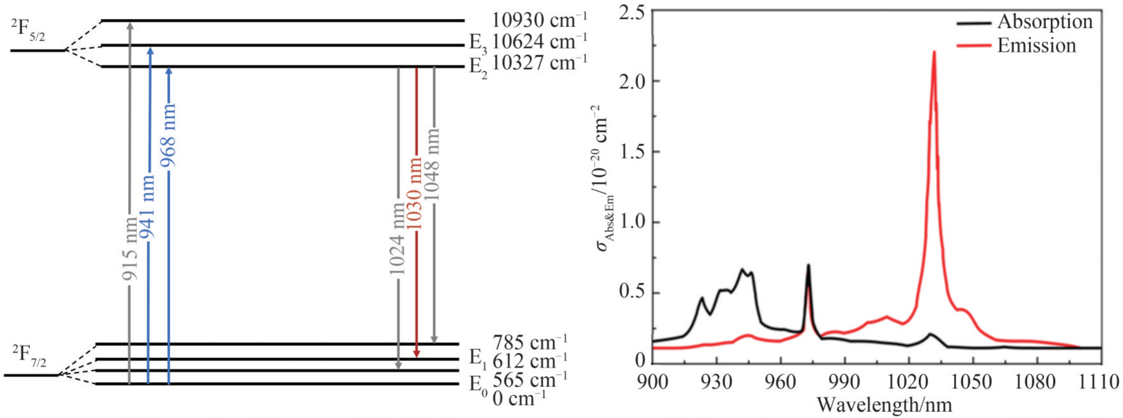
另一方面，Yb∶YAG晶体表现出的优异特性如宽泵浦带宽、长荧光寿命、高质量生长和高热导率等特点，使其成为目前最成熟的薄片晶体材料。Yb∶YAG晶体在波长940 nm处及969 nm处具有较强的吸收峰，在940 nm波长附近进行宽带泵浦吸收，量子损耗为8.7%。在969 nm波长附近泵浦，可以将量子损耗进一步降低至5.9%，热负荷将降低30%以上。然而，在969 nm处吸收线宽仅约1 nm，这对半导体泵浦激光器有极高的要求。随着体布拉格光栅（Volume Bragg Grating，VBG）在半导体激光器的应用，采用波长锁定的969 nm零声子线泵浦成为有效解决方案[19]。2021年，D+G公司报道了采用969 nm“零声子线”（Zero Phonon Line，ZPL）泵浦的高功率薄片激光器，实现了2.8 kW的连续激光输出，光-光转化效率高达80%[20]。

国内薄片激光器的相关研究起步较晚，但发展迅速。2011年，中国工程物理研究院王春华研究员等采用16冲程940 nm泵浦，获得了27 W的连续薄片激光输出，光-光转化效率为38.8%[21]。华中科技大学朱晓教授课题组[22]提出了共轭双抛物面镜的多通泵浦结构，并开展了大量研究。2016年，该课题组基于48冲程940 nm泵浦方案，实现了654 W的高功率激光输出和47.2%的光-光转化效率[23]。2022年，中国科学院大连化学物理所李刚研究员课题组报道了基于72冲程969 nm泵浦系统的连续薄片激光器，最终输出243.2 W的连续激光，光-光转化效率达到了54%[24]。

目前国内薄片激光器核心器件仍然发展不足，尤其是薄片晶体和泵浦系统。因此，研制高性能的薄片晶体和泵浦模块，对于实现高功率、高能量和高光束质量的激光输出意义重大。本文采用体布拉格光栅锁波长的969 nm泵浦源和自主设计的48冲程系统对Yb∶YAG薄片晶体进行研究，实现了最高输出功率373 W，光-光转化效率可达73.37%，2 h功率抖动均方根（Root Meam Square，RMS）测试结果低于0.2%。本文研究为后续开展千瓦级超快和万瓦级连续薄片激光器研究奠定了基础。

## 1　Yb∶YAG薄片晶体及多冲程泵浦模块

Yb∶YAG晶体表现出的优异特性使其成为高功率激光活性材料的理想选择[25]。Yb∶YAG具有简单的能级结构，仅由间距约10 000 $\mathrm{cm^{-1}}$的基态能级$^2F_{7/2}$和受激多重态$^2F_{5/2}$两个能级组成。在强晶场作用下，抽运和激光跃迁发生在Stark分裂的子能级之间，如图1（a）。其中，激发态能级$^2F_{5/2}$中的10 327 $\mathrm{cm^{-1}}$能级的荧光寿命很长，约0.91 ms，能够较好地储存能量，而$^2F_{7/2}$基态能级中的612 $\mathrm{cm^{-1}}$能量较大，主要的1 030 nm激光辐射发生在这两个子能级之间。图1（b）为Yb∶YAG的吸收和发射光谱图，Yb∶YAG晶体有两个主要的吸收峰：在940 nm附近吸收最强，在969 nm附近吸收带宽较窄。但与940 nm泵浦相比，采用969 nm泵浦可降低量子损耗，进而减小晶体的热透镜和热畸变效应，提高输出激光光束质量[19, 26]。Yb∶YAG在969 nm较窄



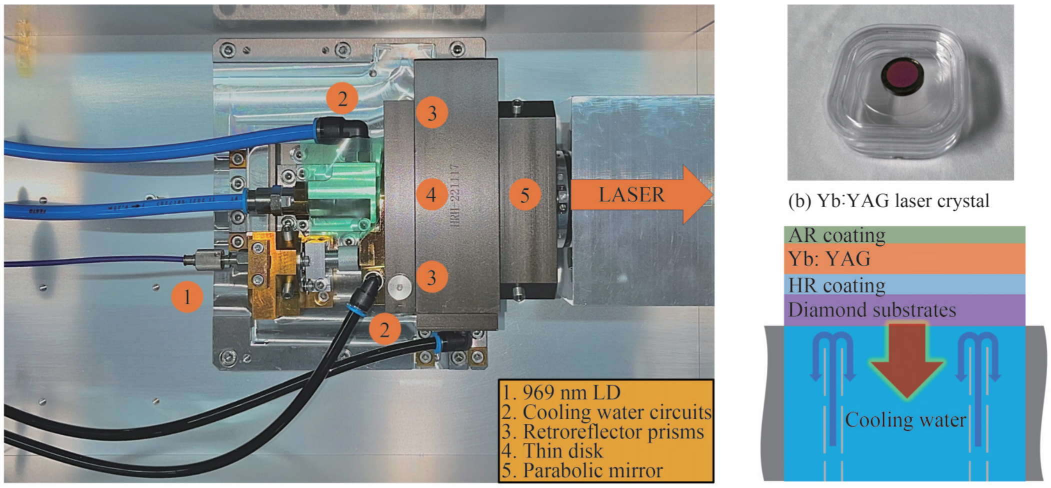
(a) Energy level diagrams of Yb: YAG　　(b) Absorption and emission spectrum of Yb: YAG

图1　Yb∶YAG能级结构及吸收、发射光谱

Fig. 1　Energy level structure and spectrum of Yb∶YAG

的吸收线宽（约1 nm），要求半导体泵浦激光器的发射线宽匹配且稳定。随着体布拉格光栅在半导体激光器中的应用，采用波长锁定的969 nm零声子线泵浦[27,28]成为实现高功率、高效率薄片激光器的有效方法。

自主设计的48冲程泵浦系统及薄片晶体如图2。晶体前端面镀有抗反射膜层，后端面镀有高反射膜层。为了提高薄片晶体的散热效率，将其键合至金刚石衬底上。金刚石是薄片晶体的理想衬底[29]，其热导率达2 200～2 600 W/（m·K），是已知自然界中热导率最高的物质。其优良的键合效果可以实现较好的热接触和低热阻，同时具有高机械强度。通过射流冲击技术高效冷却金刚石热沉，冷却水通过空间分布的孔槽以一定水压直接冲击金刚石衬底，以对流换热的方式带走表面上的热量。水压与流速可控，温度恒定。该冷却装置具有结构紧凑、传热系数高、散热区域均匀等优点。由于薄片晶体接近一维分布的热梯度、金刚石极高的热导率以及高效的射流冲击散热，高功率泵浦过程中薄片晶体产生的废热可以得到有效缓解，有利于提升输出激光的稳定性、光束质量等，最终实现更高功率、更高转化效率的薄片激光输出。



(b) Yb:YAG laser crystal

(a) Physical diagram of multiple-pass pumping scheme

(c) Schematic diagram of thin disk crystal

图2　自研多冲程泵浦系统和薄片晶体

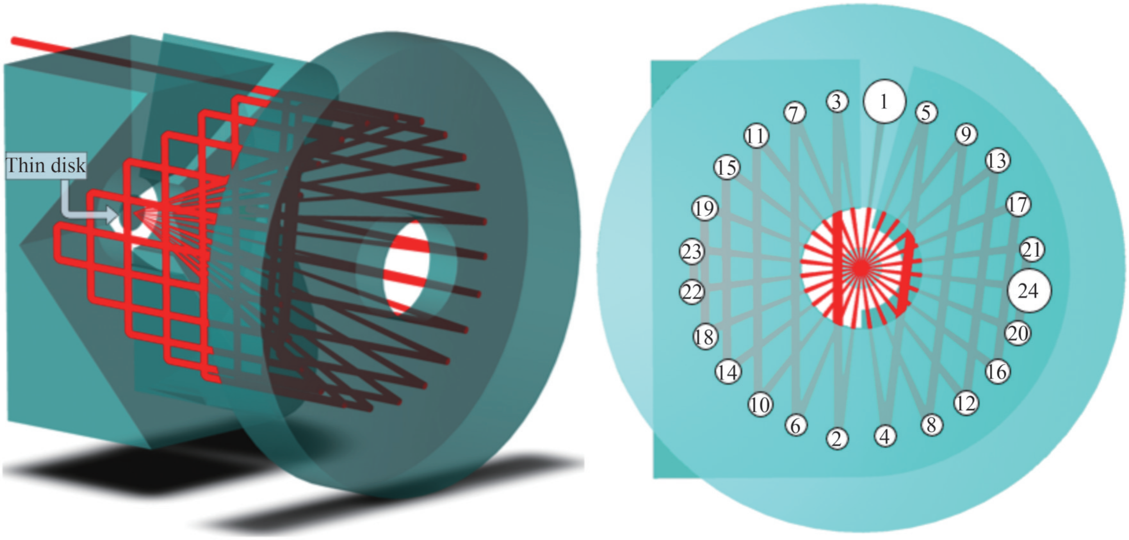
Fig. 2　Self developed multiple-pass pumping system and the crystal

48冲程泵浦系统的内部结构及泵浦光线分布如图3（a）～（c），该系统主要由泵浦源、抛物面镜和两对折返棱镜组成。薄片晶体位于抛物面镜的焦平面上。准直的泵浦光束入射至抛物面镜的位置1，经反射聚焦到晶体上，未被吸收的泵浦光经晶体反射到达抛物面镜的位置2再次准直，经过折返棱镜到达抛物面镜的位置3再次聚焦到晶体上。利用折返棱镜和抛物面镜的其他区域，泵浦光可以在薄片晶体上实现12次反射，即往返通过薄片晶体24次，最后通过一个平面反射镜将泵浦光路径反向，最终实现48冲程吸收。该泵浦系统可以将单次未被完全吸收的泵浦光经过由抛物面镜及折返棱镜组成的光学系统多次入射到晶体上，增加泵浦光通过薄片晶体的冲程数，从而提高晶体的吸收效率，显著提升激光器的输出性能。此外，泵浦光在薄片晶体上的重叠程度，决定了泵浦光斑的平均功率密度，进而影响激光器的整体输出功率和效率。图3（d）为系统在高功率工作状态下薄片晶体上的光斑分布。可见泵浦光在晶体上叠加24次后充分重合，且均匀性良好，证明该泵浦系统具有良好的调节精密性和机械稳定性。

当晶体厚度、$\mathrm{Yb}^{3+}$掺杂浓度以及晶体前后表面反射率确定时，高冲程系统可以有效提高薄片晶体对泵浦光的吸收效率。冲程次数过高会增加系统的加工难度，而过低则难以实现薄片晶体对泵浦光的高效吸收。基于朗伯比尔定律，晶体的吸收效率$\eta$与泵浦冲程次数$N$的关系[30-31]可表示为

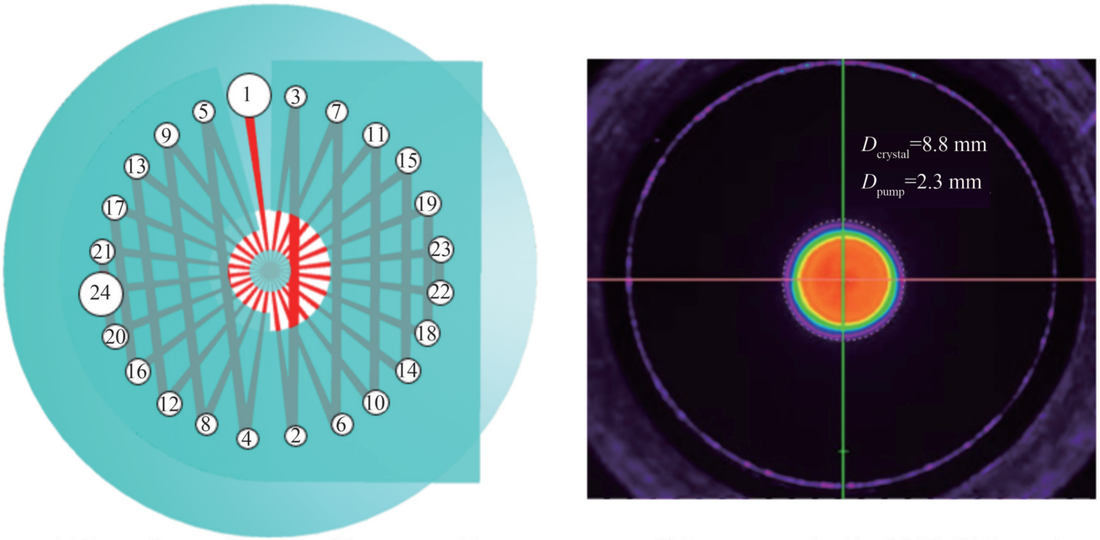
$$\eta=R(1-A)(1+RA)\frac{1-(R^{5}A^{2})^{\frac{N}{2}}}{1-(R^{5}A^{2})} \tag{1}$$

式中，光学元件对泵浦光的反射率$R=99.95\%$@969 nm@0°～30°，$A=\mathrm{e}^{-\alpha L/\cos\theta}$，Yb：YAG薄片晶体的吸收系数$\alpha$为0.42/mm，薄片晶体的厚度$L=150\ \mu\mathrm{m}$，泵浦光对薄片晶体的入射角$\theta=30°$，冲程次数$N=48$。通过式（1）计算可得泵浦冲程次数、不同单程吸收率和薄片晶体吸收效率的关系，如图4。可见，受离子掺杂浓度



(a) Schematic diagram of simulated pump light

(b) Parabolic mirror view of the pump module



(c) Retroreflector prisms view of the pump module

(d) Pump spot on the thin-disk Yb:YAG crystal

图 3　泵浦模块原理及薄片晶体上的泵浦光斑

Fig. 3　Schematic of the pump module and the pump light spot on the crystal

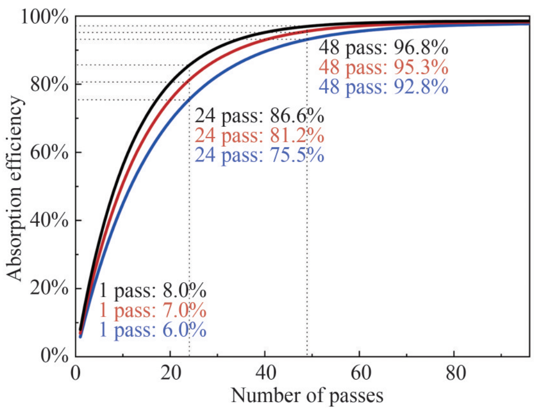


图 4　薄片晶体吸收效率与泵浦冲程次数的关系

Fig. 4　Absorption efficiency of thin-disk crystal versus number of pump passes

影响的吸收系数$\alpha$以及冲程次数$N$对薄片晶体的吸收效率影响较大。随着泵浦光通过晶体次数的增加，晶体吸收效率随之增大，冲程次数增加到一定程度时，晶体吸收效率趋于饱和。晶体总吸收率随着晶体单程

吸收率的增大而增大，在低冲程下影响较为显著，当冲程次数达到48次时，晶体吸收效率基本稳定。该泵浦系统平衡了加工难度、晶体热效应和吸收效率的关系，实现了晶体对泵浦光的高效吸收，可长时间稳定工作。

## 2 实验结果与讨论

薄片激光器结构如图5，激光器由48冲程泵浦模块和透过率为2%，曲率半径$R$为2 000 mm的输出耦合镜组成，腔长为0.75 m，构成平-凹腔，实现稳定激光输出。增益介质为Yb:YAG圆盘状薄片晶体，直径为8.8 mm，键合于金刚石热沉，水冷温度保持在20 ℃。晶体前端面镀有969 nm、1 030 nm抗反射膜层（$R<0.1\%$@0°～30°），后端面镀有高反射膜层（$R>99.9\%$@0°～30°）。泵浦源采用半导体激光二极管（Laser Diode, LD），其输出特性如图6(a)、(b)，最高输出功率为520 W，中心波长为968.9 nm，且带宽小于1 nm，满足Yb:YAG零声子线泵浦的窄线宽要求。泵浦光经过匀化光纤整形为平顶光斑，通过准直镜和抛物面反射镜以30°入射角重新成像在薄片晶体上，在晶体上的光斑直径为2.3 mm，较大的泵浦光尺寸可以提高系统的散热效率，有效防止功率密度过高损伤薄片晶体，有利于高功率激光器的长时间稳定运作。

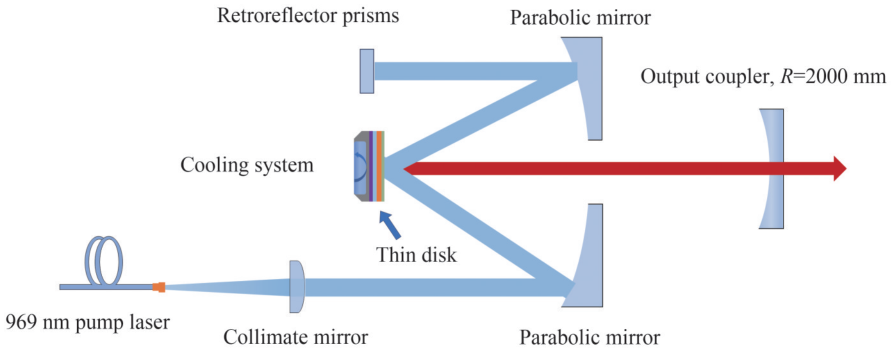
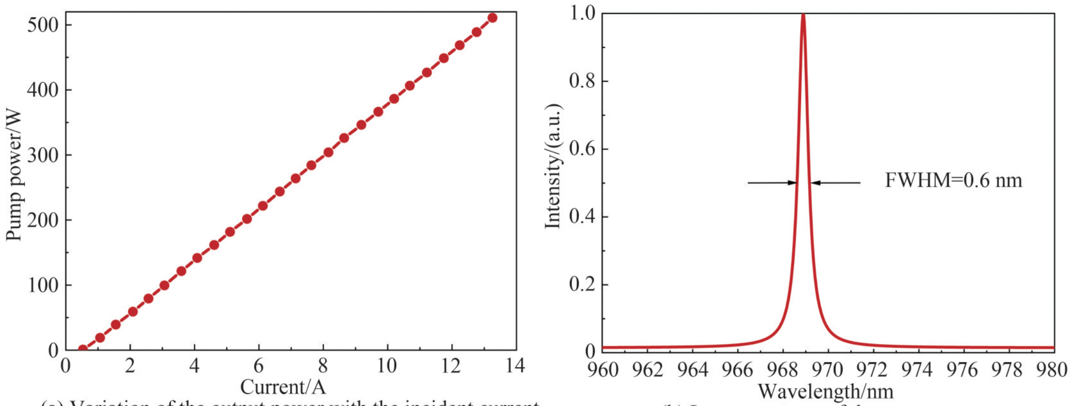


图5 基于48冲程泵浦系统的Yb:YAG薄片激光器结构

Fig. 5 Schematic of the Yb:YAG thin disk laser based on the 48-passes pumping system



(a) Variation of the output power with the incident current

(b) Laser spectrum of the pump source

图6 泵浦源输出特性

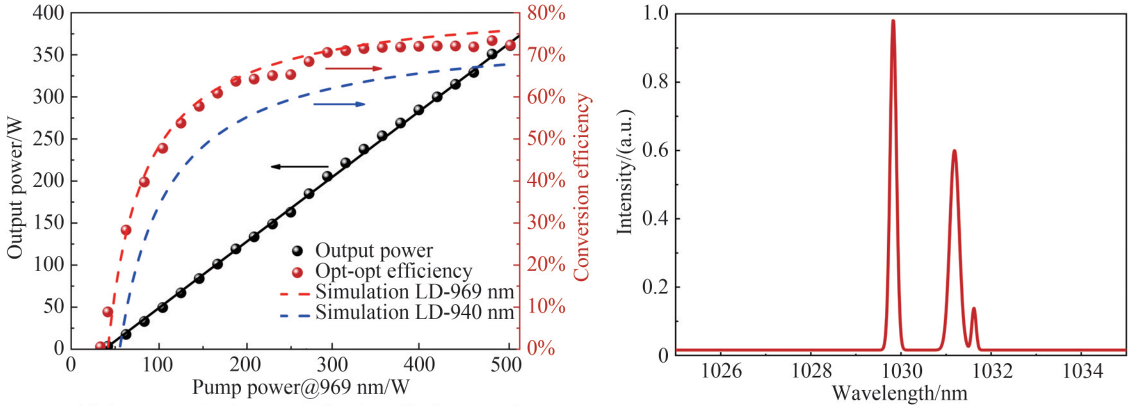
Fig. 6 Output characteristics of the pump source

激光器的光-光转化效率$\eta_{\mathrm{opt}}$主要受晶体吸收效率$\eta_{\mathrm{abs}}$、谐振腔效率$\eta_{\mathrm{cavity}}$、量子转换效率$\eta_{\mathrm{st}}$以及阈值效率$\eta_{\mathrm{th}}$的影响[20,32]，可表示为

$$\eta_{\mathrm{opt}}=\eta_{\mathrm{cavity}}\cdot\eta_{\mathrm{st}}\cdot\eta_{\mathrm{abs}}\cdot\eta_{\mathrm{th}} \tag{2}$$

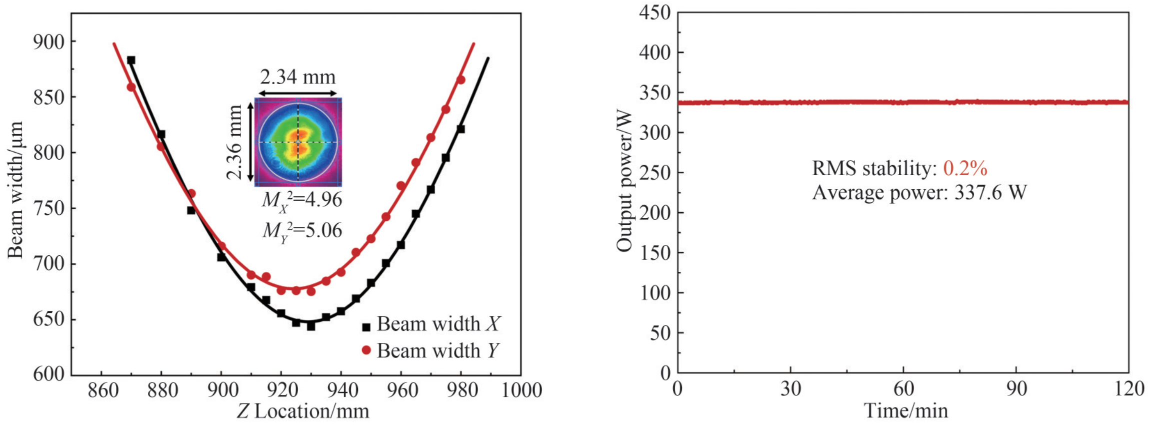
式中，$\eta_{\mathrm{th}}=1-p_{\mathrm{th}}/p_{\mathrm{pump}}$，$p_{\mathrm{th}}$为阈值泵浦功率，$p_{\mathrm{pump}}$为泵浦功率。高冲程泵浦系统的设计对谐振腔效率和晶体吸收效率有明显提升。Yb:YAG薄片晶体中的废热是影响转化效率的一个重要因素，而废热的主要来源是量子亏损。选用969 nm最佳泵浦波长将提升量子转化效率，减少晶体中的废热，同时降低阈值泵浦功率，提升阈值效率，在这些因素的综合影响下，可以得到较高的光-光转化效率。

通过式(2)计算比较了969 nm与940 nm两种不同泵浦波长对Yb:YAG薄片激光器转换效率的影响，结果表明采用969 nm零声子线泵浦，光-光转化效率会有显著提升。光-光转化效率曲线如图7(a)，低泵浦功率限制了基态粒子的吸收能力，这阻碍了激发态粒子的积累，激光器表现为较低的光-光转化效率。随着泵浦功率增加，腔内微弱的自发辐射场增长为足够强的受激辐射场，吸收和发射过程变得更为显著，光-光转化效率迅速提高。当泵浦功率持续增加至300 W，受增益饱和影响，效率曲线趋于稳定。当泵浦功率接近480 W时，由于晶体的泵浦漂白效应，转化效率出现小幅下降，但依然维持在70%以上。实验中获得了最高373 W的输出功率，最大光-光转化效率为73.37%，经线性拟合后斜效率为78.97%。图7(b)为激光器的输出光谱，可见光谱呈现多个峰值且强度不同，这是由于连续波激光器中含多种模式，这些模式具有不同的频率和振幅，每个模式都会在输出光谱中产生一个峰值。不同模式之间存在竞争，会导致一些模式的增益增加，而其他模式的增益减小，从而引起不同峰值的强度差异。图7(c)为该激光器在最高功率下的光束质量$M^2$因子和近场光斑形貌，实际的激光输出含有高阶模态，$M_X^2=4.96$，$M_Y^2=5.06$，输出光斑的均匀性良好。图7(d)为该激光器高功率运转120 min稳定性测试曲线，结果表明该激光器在337.6 W附近稳定工作，功率抖动均方根小于0.2%，因此，该激光器在高功率运转过程中散热性能良好，具有较高的稳定性。



(a) Average output power and opto-optical conversion efficiency under different pump modes

(b) Output spectrum of CW thin disk laser



(c) Beam qualityfactor $M^2$ and near-field spot profile at 373 W

(d) Stability of output power

图7　Yb:YAG连续薄片激光器输出性能

Fig. 7　Output performance of the Yb:YAG thin-disk laser

## 3　结论

本文设计并搭建了一台Yb:YAG连续薄片激光器，采用VBG锁波长的969 nm泵浦光经过自制的48冲程系统对Yb:YAG薄片晶体进行了系统研究，冷却系统采用射流直接冲击金刚石热沉，实现了最高输出功率373 W，光-光转化效率可达73.37%，2 h功率抖动均方根测试结果低于0.2%。研究结果表明，该薄片激光器系统具有高效的热管理能力，优异性能，可为后续开展万瓦级连续薄片激光器、千瓦级绿光激光及超快薄片激光研究奠定基础。

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# High Efficiency Yb∶YAG Thin Disk Laser Based on Zero Phonon Line Pumping

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**Abstract:** There is a growing demand for high-power lasers in industries such as laser cutting, welding, heat treatment, and marking. High efficiency oscillators with scalable power have the potential to streamline the system complexity and cost per Watt compared to amplification stages. The main challenge for power scaling is the heat load on the gain medium. Yb∶YAG crystals are attractive gain mediums because they offer high thermal conductivity, wide pump bands, low quantum defects, relatively long fluorescent lifetime, and high-quality crystal growth. Their energy-level scheme eliminates the problem of excited-state absorption, which makes the quantum defect become the primary heat source in the crystal. Complementing these advantages with suitable architectures with high surface-to-volume ratios such as fiber and Thin-disk Lasers (TDLs) enables excellent heat extraction. However, fiber lasers still face the challenge of nonlinear effects such as self-phase modulation and stimulated Raman scattering at high power. Alternatively, thin-disk lasers have improved the situation. We demonstrate a Yb∶YAG thin-disk laser that uses zero phonon line pumping. This type of laser system offers excellent power stability, high optical-optical conversion efficiency (>73%), and remarkable thermal management ability. Our design provides theoretical support for future research on the generation of kilowatt-level continuous and ultrafast pulses laser. We hope that our basic strategy and findings can be helpful in the design of higher power, more efficient thin-disk lasers and make them widely available in the industry.

The Yb∶YAG crystal is simple in its energy level configuration, with only two energy states of the $\mathrm{Yb}^{3+}$ ion. The absorption peaks of the crystal are at 940 nm and 969 nm, with broadband pumping achieved near 940 nm resulting in a quantum defect of 8.7%. By opting for 969 nm wavelength pumping, the quantum defect decreases to 5.9%, reducing the thermal load by over 30% and improving the beam quality by diminishing thermal lensing and distortion effects. The pump module of the experimental device consists of a pumping source, a parabolic mirror, and two sets of folding prisms. A thin-disk crystal is placed at the focal point of the parabolic mirror and undergoes 12 reflections, equating to 24 round-trip passes, as the pumping light passes through the folding prisms and mirror. The final step involves redirecting the pumping light path using a planar reflector, ultimately achieving 48-pulse absorption. The frontal side of the thin-disk crystal has an antireflection layer, and the back side has a high reflection coating. The crystal is bonded onto a diamond substrate to facilitate superior thermal contact, low thermal resistance, and high mechanical strength, and the jet impingement technology is employed to cool the diamond heat sink. This setup and efficient cooling design improves absorption efficiency and reduce crystal thermal load, significantly enhancing laser output performance. We calculated the correlation between the absorption efficiency of the crystal and the number of pump cycles. As the number of cycles increases, so does the absorption efficiency. However, the efficiency eventually reaches a saturation point after a specific number of cycles. In this case, at cycle number 48, the crystal absorbs 95.3% of the pump light, indicating that it is almost fully saturated at this point. In the experiment, the impact of two pumping wavelengths, 969 nm and 940 nm, on the conversion efficiency of a Yb:YAG thin-disk laser was analyzed. The results clearly demonstrate that the selection of the pumping wavelength can improve the quantum conversion efficiency and reduce the waste heat in the crystal. Besides, the design of the multiple pass pumping system can also significantly improve the resonator efficiency and crystal absorption efficiency. Utilizing a 969 nm zero phonon line pumping results in a reduced threshold pump power and a significant increase in optical-optical conversion efficiency. With the gradual increase in pump power, the optical-optical conversion efficiency also enhances. An output coupling experiment is performed using an output coupler with a transmission rate of 2%, and the overall structure of the laser system is also shown.

A continuous wave Yb:YAG thin disk laser system has been successfully developed, which exhibits exceptional capabilities. The system utilizes a VBG locked-wavelength 969 nm pump source and a 48-pass design. The cooling system employs jet impingement technology on a diamond heat sink. The experiment successfully achieved a maximum output power of 373 W and a peak optical-optical conversion efficiency of 73.37%. The Root Mean Square (RMS) power stability over a 2-hour period is less than 0.2%. The research shows the exceptional thermal management capabilities of this thin-disk laser system. It provides a foundation for future studies involving multi-kilowatt continuous thin-disk lasers, kilowatt-level green lasers, and ultrafast thin-disk lasers. We believe that the thin disk lasers with many advantages can be the ideal solution for the next generation of high-power, high-energy, peak-power lasers.

**Key words**: Thin-disk laser; Multi-pass pumping; Yb:YAG; High efficiency

**OCIS Codes**: 140.3580; 140.5560; 140.6810; 140.3480

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