中国激光

Tm:YLF 激光腔内泵浦2.1 μm Ho:YVO_4激光器

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摘要 研究了可常规半导体泵浦的 Tm:YLF 激光腔内泵浦 Ho:YVO_4 激光器。利用 *c*-切 Tm:YLF 晶体在 1909 nm 附近的腔内输出波长以更好地匹配 Ho:YVO_4 晶体的共振吸收带，实现了最高 3.3 W 的激光输出，中心波长为 2052.7 nm，对应的斜率效率和光光转换效率分别为 14.5% 和 11%。得益于 Tm:YLF 晶体固有的弱热透镜效应，该腔内泵浦钬激光器在最高激光功率下仍保持高的光束质量，水平方向和垂直方向的光束质量分别为 1.33 和 1.46。所设计的掺钬钒酸盐激光器经济实用，结构紧凑，且易于实现。

关键词 激光器；掺钬钒酸钇；掺铥氟化钇锂；腔内泵浦；2.1 μm

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1 引 言

2.1 μm 钬(Ho)激光器在生物医学[1]、红外光电对抗[2]、高分子材料加工[3]和中远红外非线性变频[4]等诸多领域中具有重要的应用价值。相对于主流的同带泵浦 Ho 激光器[5-7]，腔内泵浦 Ho 激光器无需额外的高性能 1.9 μm 掺铥(Tm)全固态或光纤激光泵浦源，能够在常规 800 nm 激光二极管(LD)泵浦的紧凑结构上实现高效的室温 Ho 激光输出。

在这一 Ho 激光器结构中，掺铥和掺 Ho 增益介质共同放置在谐振腔内，在常规 LD 对掺 Tm 介质的泵浦下，谐振腔内产生了 1.9 μm 激光，其对掺 Ho 介质进行同带泵浦。由于激光运行过程中没有 Tm 激光泄漏出腔外，相对于存在转换损耗的 Tm，Ho 共掺激光器[8-10]，该机制具有更高的 LD 到 Ho 激光的室温转换效率[11]。1992 年，Stoneman 等[12]首次提出了腔内泵浦 Ho 激光器，在 Tm:YAG 腔内泵浦 Ho:YAG 结构上实现了140 mW 的 2.09 μm 激光输出。由于腔内 Tm:YAG 和 Ho:YAG 晶体的组合热透镜效应，当将 Ho 激光功率提升到 7.2 W 时，激光光束质量(M^2)出现显著退化($M^2\sim6$)[13]。2016 年，Huang 等[14]通过提高腔内 Tm:YAG 激光的激发效率来提高 Ho 激光的输出效率并缓解激光器热效应，在 25 W 波长锁定 LD 泵浦下(线宽：0.1 nm，中心波长：784.9 nm)，实现了 8.03 W 的 2122 nm Ho 激光输出，光束质量进一步得到提升($M^2\sim2.7$)。由于掺 Tm 介质的热透镜效应显著高于具有低量子亏损(<10%)的掺 Ho 介质[15]，Schellhorn 等[16]首次提出了采用具有低热透镜效应的 Tm:YLF 晶体来替换 Tm:YAG 晶体，实现了 1.6 W 的高光束质量腔内泵浦 Ho 激光输出。2012 年，Zhu 等[17]通过将端面泵浦的总功率增加到 135 W，在双 Tm:YLF 晶体腔内泵浦 Ho:YAP 激光器结构中实现了8 W 的 Ho 激光输出($M^2\sim2.2$)。

此外，其他掺 Tm 和掺 Ho 介质组合的腔内泵浦方式也陆续得到研究，例如 Tm:YAG 和 Ho:$GdTaO_4$[18]、Tm:YVO_4 和 Ho:YAG[19]、Tm:YAG 和 Ho:SSO[20]、Tm:YAP 和 Ho:YVO_4[21]以及 Tm:KluW 和 Ho:KLuW[22]。在上述激光工作物质中，YLF 晶体具有负热光系数和弱热透镜效应，因此该晶体作为腔内泵浦 Ho 激光器的掺 Tm 介质，可缓解组合热透镜效应。同时，钒酸盐晶体 YVO_4 或 $GdVO_4$ 等在稀土离子掺杂下普遍具有大的发射截面和宽的荧光发射带[23]，可成为腔内泵浦机制的掺 Ho 工作物质，被广泛应用到 1 μm 激光技术研究中[24-25]。Ho 离子在腔内同带泵浦方式下的低量子亏损性能能够有效地克服钒酸盐晶体本身的低热导率和低热损伤阈值的影响，这已在若干腔外同带泵浦 Ho:YVO_4 激光器中得到了证明[26-28]。然而，基于该类晶体，可常规 LD 直接泵浦的腔内泵浦 Ho 激光的机制研究较少。2020 年，Hu 等[21]首次对腔内泵浦 Ho:YVO_4 激光器进行了报道，在 Tm:YAP 激光的泵浦下，初步实

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现了最高 1.7 W 的 2052 nm Ho 激光输出，斜率效率(SE)为 10.4%。但受限于 Tm∶YAP 晶体的强热透镜效应，腔内泵浦 Ho∶YVO_4 的激光功率和效率有待进一步提升。

本文采用具有负热透镜效应的 Tm∶YLF 晶体来缓解腔内泵浦 Ho∶YVO_4 激光器的组合热透镜效应，获得了最高 3.3 W 的 2052 nm Ho 激光输出，斜效率达 14.5%，LD 到 Ho 激光的光光转换效率为 11%。据我们所知，这是目前腔内泵浦掺 Ho 钒酸盐激光器的最高激光功率和激光效率。

2　实验设计与装置

采用紫外-可见-近红外分光光度计测量了 Tm 原子数分数为 3% 的 Tm∶YLF 和 Ho 原子数分数为 0.6%的 Ho∶YVO_4 晶体样品的偏振吸收光谱，用于评估腔内 Tm∶YLF 激光和 Ho∶YVO_4 晶体吸收带的光谱交叠情况。其中，Tm∶YVO_4 晶体的偏振发射光谱是基于所测量的吸收光谱换算得出的[29]。如图 1 所示，Tm∶YLF 晶体沿 π 偏振和 σ 偏振方向的荧光发射峰分别在1881 nm 和 1905 nm 处，与 Ho∶YVO_4 晶体的偏振吸收带基本重叠。该吸收带覆盖的波长范围是从 1906 nm 到 1972 nm，对应的吸收峰分别为 1933 nm 和 1954 nm。因此，Tm∶YLF 晶体在 σ 偏振方向的荧光发射带更加匹配 Ho∶YVO_4 晶体的吸收带，有望实现高效率的腔内泵浦 Ho 激光输出。为了直接实现 σ 偏振方向的腔内 Tm 激光输出，所采用的 Tm∶YLF 晶体将沿 c 轴方向进行切割。

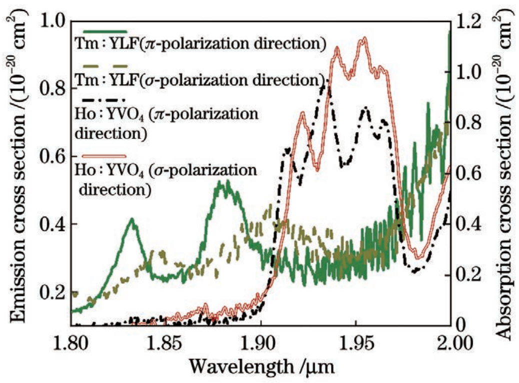

图 1　Tm 原子数分数为 3%的 Tm∶YLF 晶体的偏振发射光谱和 Ho 原子数分数为0.6%的 Ho∶YVO_4 晶体的偏振吸收光谱

Fig. 1　Polarized emission spectra of Tm∶YLF crystal with Tm atomic fraction of 3% and polarized absorption spectra of Ho∶YVO_4 crystal with Ho atomic fraction of 0.6%

图 2 为所设计的腔内泵浦 Ho∶YVO_4 激光器，分别采用尺寸为 3 mm×3 mm×14 mm、Tm 原子数分数为 3% 的 c 切 Tm∶YLF 晶体和尺寸为3 mm×3 mm×4 mm 、Ho 原子数分数为 3% 的 a 切 Ho∶YVO_4晶体。为了进一步简化腔内泵浦 Ho 激光器结构，在 Tm∶YLF 晶体的泵浦端面镀高反@1.8～2.2 μm 且增透@760～850 nm 的膜层，充当激光器的后谐振腔镜。两块晶体的其他端面均镀增透@1.8～2.2 μm 的膜层。Tm∶YLF 和 Ho∶YVO_4 晶体均用铟箔包裹并被封装在同一块热沉中进行水冷控温，冷却温度设置为 16 ℃。激光泵浦源为中心波长在 792 nm、最高功率达 30 W 的光纤耦合 LD 模块，光纤的芯径为 400 μm，数值孔径为 0.22。通过两块焦距均为 40 mm 的平凸透镜(F1)将泵浦光斑聚焦到 Tm∶YLF 晶体内部。因此，采用对 Tm 激光(波长为 1.80～2.02 μm)高反、对 Ho 激光 (波长为 2.05～2.12 μm)的透过率为 10%的窄带耦合输出镜(OC)。OC 的曲率半径为 200 mm，与 Tm∶YLF 晶体的泵浦端面构成长度为35 mm 的平凹腔。采用热释电功率计对 2 μm 激光功率进行测量，采用中红外光谱仪对激光波长进行测量，采用光束质量分析装置对腔内泵浦 Ho 激光的光束质量进行测量。

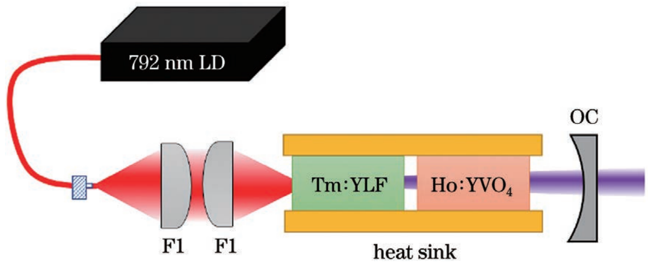

图 2　Tm∶YLF 激光腔内泵浦 Ho∶YVO_4 激光器的实验装置图

Fig. 2　Experimental setup of Tm∶YLF laser intra-cavity pumped Ho∶YVO_4 laser

3　实验结果与讨论

在进行腔内泵浦 Ho 激光实验前，撤去热沉中的 Ho∶YVO_4 晶体，将窄带耦合输出镜替换为在 1.80～2.12 μm 波段的透过率为 10%、曲率半径为 200 mm 的平凹宽带耦合输出镜，对 Tm∶YLF 晶体的激光效率进行测量。如图 3 所示，在 792 nm LD 的入射功率为 30 W 时实现了 11.38 W 的 Tm∶YLF 激光输出，斜

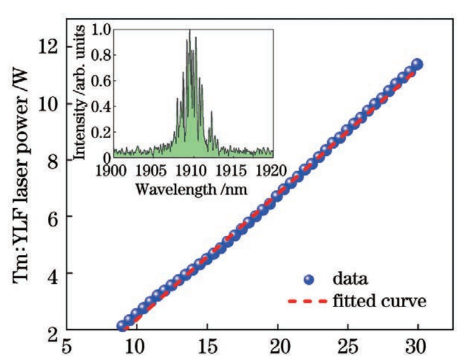

图 3　c 切 Tm∶YLF 激光器的输出功率(插图：最高激光功率下的输出光谱)

Fig. 3　Output power of c-cut Tm∶YLF laser with output spectrum at maximum laser power shown in inset

率效率达 44.3%，光光转换效率为 37.9%。最高 Tm 激光功率下测得激光中心波长为 1909.7 nm，该激光波长对应 Tm∶YLF 晶体沿 *a* 轴方向的荧光发射带（σ 偏振）。

进一步开展腔内泵浦 Ho∶YVO_4 激光器研究。在 8.5 W 792 nm 泵浦功率下，激光器开始振荡并在最高 30 W 泵浦入射功率下获得最高 3.3 W 的 Ho∶YVO_4 激光输出，对应 LD 到 Ho 激光的光光转换效率达 11%［图 4(a)］。拟合得出的 Ho 激光的斜率效率达 14.5%，显著高于 Tm∶YAP 腔内泵浦 Ho∶YVO_4 激光器的斜率效率（10.4%）[21]。在阈值泵浦功率（8.5 ～ 9.8 W）附近测得泄漏出的 1909 nm Tm∶YLF 激光，随后 Tm 激光信号消失，Ho∶YVO_4 激光开始起振［图 4(b)］。在输出功率增大过程中，Ho 激光的输出波长稳定在（2052.2±0.5）nm，未测得残留的 Tm 激光信号。这一现象可以解释为：在阈值附近，Ho 激光开始起振，消耗的腔内 Tm 激光能量有限，进而能够观察到 Tm 激光信号。随着 Ho 激光功率的增加，消耗的腔内 Tm 激光能量增加。此时，腔内 Tm 激光进入新的稳态，即 LD 泵浦所产生的增益与 Ho∶YVO_4 晶体的共振吸收损耗保持平衡。相对于 Ho 激光的强信号，泄露的 Tm 激光信号很弱，被淹没在光谱噪声中。测得最高 Ho 激光功率下水平方向的光束质量（M_x^2）和垂直方向的光束质量（M_y^2）分别为 1.33 和 1.46（图 5）。

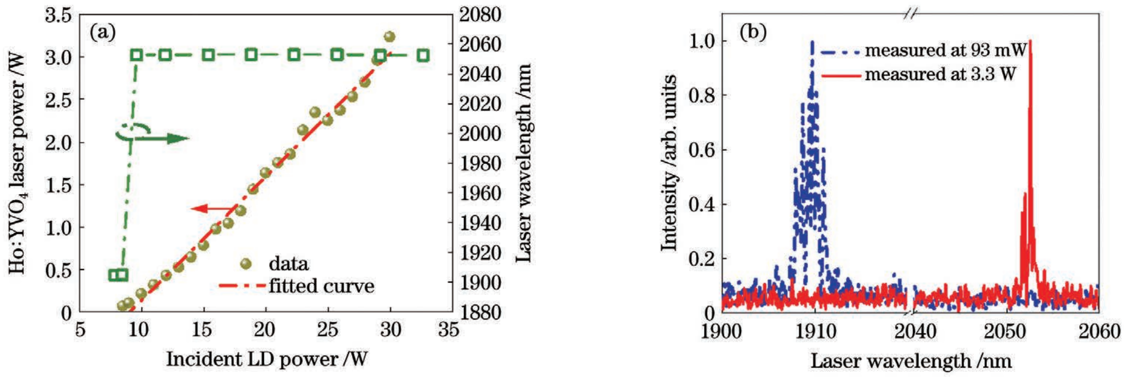

图 4 实验结果。(a)腔内泵浦 Ho∶YVO_4 激光器的输出功率和不同泵浦功率下测得的激光波长；(b)激光阈值功率和最高输出功率下测得的输出光谱

Fig. 4 Experimental results. (a) Output powers of the intra-cavity pumped Ho∶YVO_4 laser and laser wavelengths measured at different pump powers; (b) output spectra measured at laser threshold power and highest output power

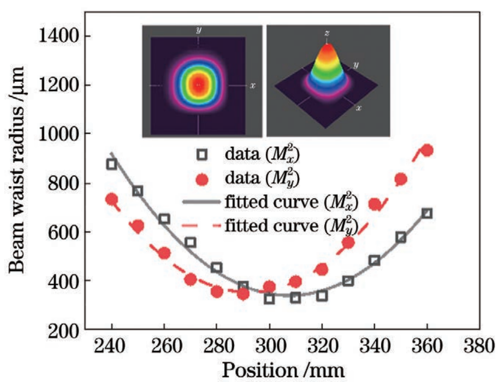

图 5 腔内泵浦 Ho∶YVO_4 激光器在最高输出功率下测得的光束质量（插图：二维和三维远场光斑轮廓）

Fig. 5 Measured beam quality of intra-cavity pumped Ho∶YVO_4 laser at maximum output power with 2D and 3D far-field spot profiles shown in inset

4 结 论

设计了结构紧凑且可用常规激光二极管直接泵浦的 Tm∶YLF 激光腔内泵浦 Ho∶YVO_4 激光器。为了实现腔内 Tm∶YLF 激光波长与 Ho∶YVO_4 晶体吸收带的高效重叠，采用沿 *c* 轴方向切割的 Tm∶YLF 晶体，最终实现了 1909 nm 波长附近的 σ 偏振 Tm 激光输出，这在腔内泵浦 Ho 激光实验中得到了验证。在 Tm∶YLF 激光实验中实现了最高11.3 W 的 1910 nm Tm 激光输出，对应的斜率效率达 44.3%，光光转换效率为 37.9%；在腔内泵浦 Ho∶YVO_4 激光实验中实现了最高 3.3 W 的 2052 nm 激光输出。所采用的 Tm∶YLF 晶体的弱热透镜效应保证了高光束质量的腔内泵浦 Ho∶YVO_4 激光输出。上述结果表明，可以通过腔内泵浦的方式，在常规 LD 的直接泵浦下，在掺 Ho 钒酸盐晶体上实现瓦级的室温 Ho 激光输出。

参 考 文 献

[1] Cheng Y, Wang G F, Zhang W, et al. Feasibility and long-term safety of Ho∶YAG laser lithotripsy in broncholithiasis patients [J]. BMC Pulmonary Medicine, 2021, 21(1): 81.

[2] Elder I. Performance requirements for countermeasures lasers [J]. Proceedings of SPIE, 2010, 7836: 783605.

[3] Astrauskas I, Považay B, Baltuška A, et al. Influence of 2.09-μm pulse duration on through-silicon laser ablation of thin metal coatings[J]. Optics & Laser Technology, 2021, 133: 106535.

[4] 魏磊，吴德成，刘东，等. Ho∶YLF 激光泵浦的长波红外 $ZnGeP_2$ 光参量振荡器[J]. 中国激光，2021, 48(1): 0101002.
Wei L, Wu D C, Liu D, et al. Long-wave infrared $ZnGeP_2$ optical parametric oscillator pumped by Ho∶YLF laser[J]. Chinese Journal of Lasers, 2021, 48(1): 0101002.

[5] Zhao T, Wang F, Shen D Y. High-power Ho∶YAG laser wing-pumped by a Tm∶fiber laser at 1933 nm[J]. Applied Optics, 2015, 54(7): 1594-1597.

[6] Ji E C, Liu Q, Hu Z Y, et al. High-power, high-energy Ho∶

YAG oscillator pumped by a Tm-doped fiber laser[J]. Chinese Optics Letters, 2015, 13(12): 121402-121406.

[7] Shen Y J, Yao B Q, Duan X M, et al. 103 W in-band dual-end-pumped Ho:YAG laser[J]. Optics Letters, 2012, 37(17): 3558-3560.

[8] 蔡宇航, 张俊旋, 陈晓, 等. 侧面抽运(Tm, Ho):YLF 晶体传导冷却百纳秒脉冲激光器[J]. 中国激光, 2021, 48(13): 1301005.
Cai Y H, Zhang J X, Chen X, et al. Side-pumped, conductively cooled (Tm, Ho):YLF pulsed laser with more than one-hundred-nanosecond pulse width[J]. Chinese Journal of Lasers, 2021, 48(13): 1301005.

[9] Yao B Q, Li G, Meng P B, et al. High power diode-pumped continuous wave and Q-switch operation of Tm, Ho:YVO_4 laser [J]. Laser Physics Letters, 2010, 7(12): 857-861.

[10] Rustad G, Stenersen K. Modeling of laser-pumped Tm and Ho lasers accounting for upconversion and ground-state depletion [J]. IEEE Journal of Quantum Electronics, 1996, 32(9): 1645-1656.

[11] Eichhorn M. Quasi-three-level solid-state lasers in the near and mid infrared based on trivalent rare earth ions[J]. Applied Physics B, 2008, 93(2): 269-316.

[12] Stoneman R C, Esterowitz L. Intracavity-pumped 2.09-μm Ho:YAG laser[J]. Optics Letters, 1992, 17(10): 736-738.

[13] Hayward R A, Clarkson W A, Hanna D C. High-power diode-pumped room-temperature Tm:YAG and intracavity-pumped Ho:YAG lasers[C]//Advanced Solid State Lasers 2000, February 13, 2000, Davos, Switzerland. Wahington, D. C.: OSA, 2000: MB8.

[14] Huang H Z, Huang J H, Liu H G, et al. Efficient 2122 nm Ho:YAG laser intra-cavity pumped by a narrowband-diode-pumped Tm:YAG laser[J]. Optics Letters, 2016, 41(17): 3952-3955.

[15] Huang H Z, Huang J H, Liu H G, et al. Manipulating the wavelength-drift of a Tm laser for resonance enhancement in an intra-cavity pumped Ho laser[J]. Optics Express, 2018, 26(5): 5758-5768.

[16] Schellhorn M, Hirth A, Kieleck C. Ho:YAG laser intracavity pumped by a diode-pumped Tm:YLF laser[J]. Optics Letters, 2003, 28(20): 1933-1935.

[17] Zhu G L, He X D, Yao B Q, et al. Ho:YAP laser intra-cavity pumped by a diode-pumped Tm:YLF laser[J]. Laser Physics, 2012, 23(1): 015002.

[18] Zhang W S, Li L J, Gao Q, et al. Efficient continuous-wave Ho:GTO laser intracavity-pumped by an in-band pumped Tm:YAG laser[J]. Infrared Physics & Technology, 2021, 118: 103849.

[19] Hu H W, Huang H Z, Huang J H, et al. Tm:YVO_4 laser intra-cavity pumped 2.1 μm Ho laser[J]. Optics Communications, 2020, 472: 125748.

[20] Duan X M, Li L J, Zheng L H, et al. Efficient intracavity-pumped Ho:SSO laser with cascaded in-band pumping scheme [J]. Infrared Physics & Technology, 2018, 94: 7-10.

[21] Hu H W, Huang H Z, Ge Y, et al. Compact intracavity-pumped Ho:YVO_4 laser developed using a diode-pumped Tm:YAP laser[J]. Optical Engineering, 2020, 59(9): 096106.

[22] Serres J M, Loiko P A, Mateos X, et al. Ho:KLuW microchip laser intracavity pumped by a diode-pumped Tm:KLuW laser [J]. Applied Physics B, 2015, 120(1): 123-128.

[23] 于浩海, 王正平, 徐民, 等. 钒酸盐系列激光晶体进展[J]. 人工晶体学报, 2012, 41(S1): 128-136.
Yu H H, Wang Z P, Xu M, et al. Research progress on vanadate series crystals[J]. Journal of Synthetic Crystals, 2012, 41(S1): 128-136.

[24] 王健, 戴腾飞, 刘海洋, 等. 基于石墨烯器件的脉宽可控被动调 Q Nd:YVO_4 激光器[J]. 激光与光电子学进展, 2021, 58(15): 1516021.
Wang J, Dai T F, Liu H Y, et al. Tunable pulse width passively Q-switched Nd:YVO_4 laser based on graphene devices[J]. Laser & Optoelectronics Progress, 2021, 58(15): 1516021.

[25] 林达, 王晶, 李丙轩, 等. Nd:YVO_4激光器横模频率简并现象的研究[J]. 中国激光, 2021, 48(20): 2001003.
Lin D, Wang J, Li B X, et al. Frequency degeneracy of transverse modes in Nd:YVO_4 lasers[J]. Chinese Journal of Lasers, 2021, 48(20): 2001003.

[26] Wang R X, Yao B Q, Zhao B R, et al. Single-longitudinal-mode Ho:YVO_4 MOPA system with a passively Q-switched unidirectional ring oscillator[J]. Optics Express, 2019, 27(24): 34618-34625.

[27] Han L, Yao B Q, Duan X M, et al. Experimental study of continuous-wave and Q-switched laser performances of Ho:YVO_4 crystal[J]. Chinese Optics Letters, 2014, 12(8): 081401.

[28] Li G, Yao B Q, Meng P B, et al. High-efficiency resonantly pumped room temperature Ho:YVO_4 laser[J]. Optics Letters, 2011, 36(15): 2934-2936.

[29] McCumber D E. Einstein relations connecting broadband emission and absorption spectra[J]. Physical Review, 1964, 136 (4A): A954-A957.

Tm:YLF Laser Intracavity Pumped 2.1 μm Ho:YVO_4 Laser

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Abstract

Objective The 2.1 μm holmium (Ho) laser has important applications in biomedicine, infrared optoelectronic antagonism, polymer material processing, and mid-far infrared nonlinear frequency conversion. Compared with mainstream in-band pumped Ho lasers, the intracavity pumped Ho laser can achieve efficient room-temperature Ho laser output based on the compact pump structure of conventional 800 nm laser diode (LD) without additional high-performance 1.9 μm thulium-doped (Tm) all-solid-state or fiber laser pump sources. In this Ho laser structure, thulium-doped and Ho-doped gain media are placed together in the resonant cavity, and 1.9 μm laser is generated in the resonant cavity under the pumping of Tm medium by conventional LD, and the Ho-doped medium is pumped in the same band. Compared with

Tm and Ho co-doped lasers with conversion loss, this mechanism has a higher LD-Ho conversion efficiency at room temperature because there is no Tm laser leakage from the cavity during laser operation. In this study, by using Tm:YLF crystal with negative thermal lens effect to alleviate the combined thermal lens effect of the Ho:YVO_4 laser pumped in the cavity, the highest Ho laser output power of 2052 nm is 3.3 W, the slant efficiency is 14.5%, and the LD-Ho laser photoconversion efficiency is 11%. The acavity-pumped Ho vanadate laser has the highest laser power and laser efficiency.

Methods Polarization absorption spectra of Tm:YLF crystal sample with Tm atomic fraction of 3% and Ho:YVO_4 crystal sample with Ho atomic fraction of 0.6% are measured using a ultraviolet-vision-near-infrared spectrophotometer. It is used to evaluate the spectral overlap between the absorption bands of the Tm:YLF laser and the Ho:YVO_4 crystal in the cavity (Fig. 1). The designed intracavity pumped Ho:YVO_4 laser adopts a c-cut Tm:YLF crystal with a size of 3 mm×3 mm×14 mm and an a-cut Ho:YVO_4 crystal with a size of 3 mm×3 mm×4 mm (Fig. 2). The 2 μm laser power is measured using a pyroelectric power meter. The laser wavelength is measured using a mid-infrared spectrometer. The beam quality of the Ho laser pumped into the cavity is measured using a beam quality (M^2) analyzer.

Results and Discussions A Tm:YLF laser output of 11.38 W is obtained at 92 nm LD incident power of 30 W with a slope efficiency of 44.3% and light-to-light conversion efficiency of 37.9%. The laser center wavelength measured at the highest Tm laser power is 1909.7 nm, corresponding to the fluorescence emission band (σ polarization) along the a-axis of Tm:YLF crystal (Fig. 3). At a pump power of 8.5 W under the wavelength of 792 nm, the laser oscillates and achieves the highest Ho:YVO_4 laser output of 3.3 W, and the corresponding LD-Ho laser optical conversion efficiency reaches 11% [Fig. 4(a)]. The fitting results show that the slope efficiency of the Ho laser reaches 14.5%, which is significantly higher than that of the Tm: YAP-pumping Ho:YVO_4 laser (10.4%). The leaky 1909 nm Tm:YLF laser is detected near the threshold pumping power (8.5–9.8 W), and then the Tm laser signal disappears and Ho:YVO_4 laser starts to vibrate [Fig. 4(b)]. In the process of increasing the output power, the output wavelength of the Ho laser is stable at (2052.2±0.5) nm, and no residual Tm laser signal is detected. This phenomenon can be interpreted as follows: when the Ho laser starts to vibrate near the threshold value, the energy consumed by the Tm laser in the cavity is limited, and the Tm laser signal can be observed. With an increase in Ho laser power, the energy consumed by the Tm laser increases. At this point, the Tm laser enters a new steady state, and the gain generated by LD pumping is mainly balanced with the resonant absorption loss of the Ho:YVO_4 crystal. Compared to the strong Ho laser signal, the Tm laser leakage signal is so weak that it is drowned in spectral noise. The beam quality in the horizontal and vertical directions at the highest Ho laser power is 1.33 and 1.46, respectively (Fig. 5).

Conclusions Tm:YLF laser intracavity pumped Ho:YVO_4 laser with a compact structure and direct pumping by a conventional laser diode is reported. To achieve efficient overlap of the absorption band between the Tm:YLF laser and Ho:YVO_4 crystal, a Tm:YLF crystal cut along the c-axis is used to achieve the σ-polarized Tm laser output near 1909 nm, which is verified by the Ho laser pumped into the cavity. In the Tm:YLF laser experiment, a maximum output of 11.3 W with 1910 nm Tm laser is achieved, with a corresponding slope efficiency of 44.3% and light-to-light conversion efficiency of 37.9%. The highest 2052 nm laser output power of 3.3 W is achieved with the intracavity pumped Ho:YVO_4 laser. Owing to the weak thermal lens effect of the Tm:YLF crystal, intracavity pumped Ho:YVO_4 laser output is guaranteed with high beam quality. The above-mentioned results indicate that the room-temperature Ho laser can be pumped at the watt level from the Ho vanadate-doped crystal by the direct pumping of a conventional LD.

Key words lasers; holmium-doped yttrium vanadate; thulium-doped yttrium fluoride lithium; intracavity pumping; 2.1 μm