ISSN 1674-1056
http://cpb.iphy.ac.cn
http://iopscience.iop.org/cpb
中国物理 B
Chinese Physics
中国物理 Chinese Physics B

Continuous-wave Nd:KGd(WO_4)$_2$ single-longitudinal-mode laser

Rui-Jun Lan(兰瑞君), Guang-Hua Liu(刘广华), Huan-Huan Min(闵欢欢), Tong-Yu Dai(戴通宇), Ying-Jie Shen(申英杰), Peng-Hua Mu(穆鹏华), Cheng Ren(任承), De-Zhong Cao(曹德忠), and Xavier Mateos

Citation: Chin. Phys. B, 2021, 30 (**8**): 084201. DOI: 10.1088/1674-1056/abea99
Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Single pixel imaging based on semi-continuous wavelet transform

Chao Gao(高超), Xiaoqian Wang(王晓茜), Shuang Wang(王爽), Lidan Gou(苟立丹), Yuling Feng(冯玉玲), Guangyong Jin(金光勇), and Zhihai Yao(姚治海)

Chin. Phys. B, 2021, 30 (**7**): 074201. DOI: 10.1088/1674-1056/abe373

Beam steering characteristics in high-power quantum-cascade lasers emitting at ~4.6 μm

Yong-Qiang Sun(孙永强), Jin-Chuan Zhang(张锦川), Feng-Min Cheng(程凤敏), Chao Ning(宁超), Ning Zhuo(卓宁), Shen-Qiang Zhai(翟慎强), Feng-Qi Liu(刘峰奇), Jun-Qi Liu(刘俊岐), Shu-Man Liu(刘舒曼), and Zhan-Guo Wang(王占国)

Chin. Phys. B, 2021, 30 (**3**): 034211. DOI: 10.1088/1674-1056/abd6fe

Analysis of dark soliton generation in the microcavity with mode-interaction

Xin Xu(徐昕), Xueying Jin(金雪莹), Jie Cheng(程杰), Haoran Gao(高浩然), Yang Lu(陆洋), and Liandong Yu(于连栋)

Chin. Phys. B, 2021, 30 (**2**): 024210. DOI: 10.1088/1674-1056/abc3b4

Stable continuous-wave single-frequency intracavity frequency-doubled laser with intensity noise suppressed in audio frequency region

Ying-Hao Gao(高英豪), Yuan-Ji Li(李渊骥), Jin-Xia Feng(冯晋霞), Kuan-Shou Zhang(张宽收)

Chin. Phys. B, 2019, 28 (**9**): 094204. DOI: 10.1088/1674-1056/ab327b

Room-temperature continuous-wave interband cascade laser emitting at 3.45 μm

Yi Zhang(张一), Fu-Hui Shao(邵福会), Cheng-Ao Yang(杨成奥), Sheng-Wen Xie(谢圣文), Shu-Shan Huang(黄书山), Ye Yuan(袁野), Jin-Ming Shang(尚金铭), Yu Zhang(张宇), Ying-Qiang Xu(徐应强), Hai-Qiao Ni(倪海桥), Zhi-Chuan Niu(牛智川)

Chin. Phys. B, 2018, 27 (**12**): 124207. DOI: 10.1088/1674-1056/27/12/124207

Continuous-wave Nd:KGd$(WO_4)_2$ single-longitudinal-mode laser*

Rui-Jun Lan(兰瑞君)[1,†], Guang-Hua Liu(刘广华)[1], Huan-Huan Min(闵欢欢)[1], Tong-Yu Dai(戴通宇)[2], Ying-Jie Shen(申英杰)[1], Peng-Hua Mu(穆鹏华)[1], Cheng Ren(任承)[1], De-Zhong Cao(曹德忠)[1], and Xavier Mateos[3]

[1] *School of Opto-electronic Information Science and Technology, Yantai University, Yantai* 264005, *China*
[2] *National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin* 150001, *China*
[3] *Física i Cristal·lografia de Materials i Nanomaterials (FiCMA-FiCNA), Universitat Rovira i Virgili (URV), Campus Sescelades, c/Marcel·lí Domingo, s/n., Tarragona* 43007, *Spain*

(Received 17 January 2021; revised manuscript received 7 February 2021; accepted manuscript online 1 March 2021)

A continuous-wave Nd:KGd$(WO_4)_2$ single-longitudinal-mode laser is demonstrated with Fabry–Perot etalons in a simple linear cavity. The thermal lens effect is dramatically lowered by propagating the laser beam along the 'athermal' direction inside the laser crystal, which is very beneficial to removing the heat generated in the mode selection process. The maximum single-longitudinal-mode output power obtained is 64.8 mW at incident pump power of 4.7 W, corresponding to an optical conversion efficiency of 1.3% and a slope efficiency of 1.7%.

Keywords: continuous wave, single-longitudinal mode, Fabry–Perot etalon

PACS: 42.55.Xi, 42.60.Pk, 42.60.Fc **DOI:** 10.1088/1674-1056/abea99

1. Introduction

Solid state single-longitudinal-mode (SLM) lasers are very attractive optical sources, which can find wide applications in cold atom physics, remote sensing, high resolution spectroscopy, optical communication, quantum optics among others.[1–3] Owing to the spatial hole-burning effect, the gain in a linear cavity cannot be depleted by one longitudinal mode, thus the introduction of additional spectral loss is necessary to prevent the adjacent laser modes from oscillating. Several types of cavities are designed to eliminate spatial hole-burning, such as unidirectional ring cavity,[4–6] microchip cavity,[7,8] twisted mode laser cavity,[9,10] coupled cavity,[11] folded cavity,[12] and linear cavity with Fabry–Perot (FP) etalons. For a standing wave cavity, the FP cavity is the primary choice to realize laser frequency selection due to its easy operation and high efficiency, which have been intensively investigated.[13–15]

The Nd:KGd$(WO_4)_2$ (Nd:KGdW) crystal is known as an effective laser crystal for near-infrared solid-state lasers. Compared with other popular Nd-doped gain media, Nd:KGdW offers high stimulated emission cross-section, broad gain bandwidth, high optical damage threshold, and high Nd^{3+} ion doping level. However, the low thermal conductivity of KGdW crystal results in strong cylindrical thermal lensing.[16,17] Previous researches of Nd:KGdW lasers mainly focused on continuous wave (CW),[18] Q-switched,[19] mode-locked,[20,21] and stimulated Raman scattering laser operations[22] and there has been no Nd:KGdW SLM laser reported.

The KGdW is a biaxial crystal with three principal mutually orthogonal axes marked as N_p, N_m, and N_g, their refractive indices are ordered as $n_p < n_m < n_g$. In 2012, Loiko *et al.* studied the thermal lens properties for different-oriented KGdW crystals, and found that the minimal thermo-optic aberration light propagation direction was along the $N_g + 30°$ in the N_p–N_g plane, which is called 'athermal' direction.[23] The existence of the 'athermal' direction is due to the negative thermo-optic coefficient $\mathrm{d}n/\mathrm{d}T$, where n is the refractive index and T is the temperature. The temperature and stress-dependent refractive indices compensate for each other, resulting in a remarkably lower thermal lensing.[24–26] It is proved that the output power scaling capacity of Nd:KGdW laser becomes comparative to that of Nd:YAG laser along this 'athermal' direction.[27] The SLM operation can generate more thermal residues than the common laser operation without laser modes suppressing. It will not only influence the output/pump efficiency but also aggravate the thermal lens effect. However, the special 'athermal' direction offers the KGdW crystal further possible applications without the limitation of the severe thermal lensing effect. In this paper, using a Nd:KGdW laser rod cut along the N_g principle optical axis, we successfully demonstrate a Nd:KGdW SLM laser. The low thermal lensing effect plays an important role in facilitating the SLM operation.

2. Experimental setup

The experimental setup is shown in Fig. 1, where used a simple plane-plane resonator with a total cavity length of 85 mm. The pump source is a fiber-coupled (400 μm in diameter, NA = 0.22) laser diode with a central wavelength around 808 nm and maximum CW output power of 25 W. The pump

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11674273 and 61805209).
†Corresponding author. E-mail: lanruijun1@163.com
© 2021 Chinese Physical Society and IOP Publishing Ltd

beam is coupled into the laser crystal by two collimating lenses with 2:1 demagnification, thus the pump spot diameter in the crystal is about 200 μm. The M1 is a plane dichroic mirror: one face is AR-coated at 808 nm, and the other face is AR-coated at 808 nm and HR-coated at 1067 nm. The M2 is a plane output coupler with a transmission of 8% at 1067 nm. The laser material is a 5%-Nd-doped uncoated KGdW crystal with dimensions of 4 mm×4 mm×2.3 mm. The selection of high doping level and short length crystal is out of the consideration of both efficiency and compactness of the SLM laser. The Nd:KGdW crystal is wrapped with indium foil and held in a water-cooled copper heat sink, where the water temperature is controlled at 15 °C throughout the experiment. Two FP etalons (0.3 mm and 0.5 mm in thickness) are employed as frequency selectors. The laser spectra, output power and output FP spectrum are recorded with an ocean optics spectrometer (HR4000CG-UV-NIR), a power meter (Ophir, Nova II) and a Fabry-Perot scanning interferometer (THORLABS, SA200-18B, FSR = 1.5 GHz).

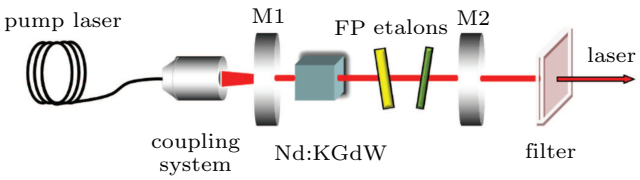


Fig. 1. Experimental setup for single-longitudinal-mode Nd:KGdW laser.

3. Results and discussion

First, we test the CW laser performance without FP etalons in the cavity. The output power of the Nd:KGdW laser as a function of incident pump power is shown in Fig. 2. The highest output power obtained is 0.5 W at incident pump power of 4.7 W, corresponding to an optical conversion efficiency of 10.6% and a slope efficiency of 12.2%.

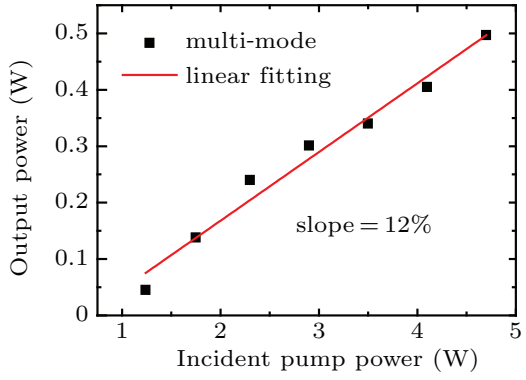


Fig. 2. Multi-mode output power of Nd:KGdW laser.

Figure 3 shows the output spectrum of the free running Nd:KGdW laser. The blue line represents the driving voltage of the piezo actuator (PZT) and the green line refers to the longitudinal modes of the output lasers, which indicates that the laser is operating in a multi-mode condition. In order to make a comparison between the multi-mode laser output power and SLM laser output power, the former is also measured with a cavity length of 85 mm. The relatively low efficiency of the free running laser may be attributed to the extra losses derived from the uncoated crystal facets and the long cavity length.

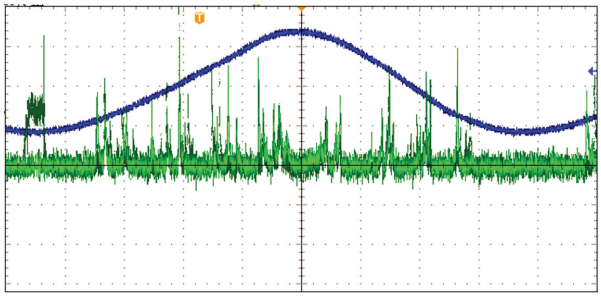


Fig. 3. Output spectrum of free-running Nd:KGdW laser.

Owing to the broad gain linewidth of the Nd:KGdW crystal, it is impossible to achieve the SLM laser by designing a micro-chip laser cavity. Luckily by using the narrowband FP etalons, the parameter window for laser cavity length can be substantially increased. The transmission curve of the etalon is determined together by its refractivity, thickness, and angles. When the refractivity is given, the thickness and angle play a leading role in obtaining a narrow transmission curve. In our experiment, we first try a single 0.5-mm thick etalon to select the longitudinal mode, but the result is not ideally good, the output spectrum shows multi-peaks inside a free spectral range. Then we insert two etalons (with 0.3 mm and 0.5 mm in thickess) into the cavity to guarantee the generation of SLM laser. After carefully tuning, we successfully achieve the SLM laser. The plot of output power *versus* incident pump power is shown in Fig. 4, showing that the highest output power is 64.8 mW at an incident pump power of 4.7 W, corresponding to an optical conversion efficiency of 1.3% and a slope efficiency of 1.7%.

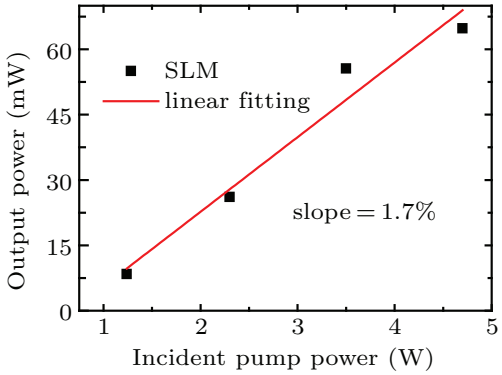


Fig. 4. Single-longitudinal-mode power characteristics of Nd:KGdW laser.

The typical time behavior of the laser spectrum is shown in Fig. 5. It can be found that only two peaks appear in a 1.5-GHz free spectral range, which indicates that an SLM operation is obtained.

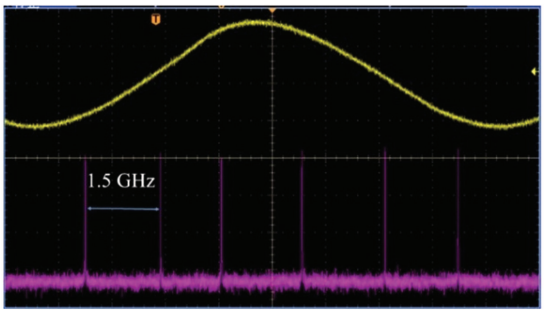


Fig. 5. FP spectra of single longitudinal mode Nd:KGdW laser.

Figure 6 shows the laser spectra of both multi-mode Nd:KGdW laser and SLM Nd:KGdW laser. The central wavelengths are both located at 1067 nm, the full width at half maximum (FWHM) of the multi-mode laser spectrum is measured to be 1.9 nm, while the SLM laser spectrum is measured to be 0.9 nm. With FP etalons inside the cavity, the laser operated in SLM condition throughout the experiment, no mode-hopping phenomenon is found.

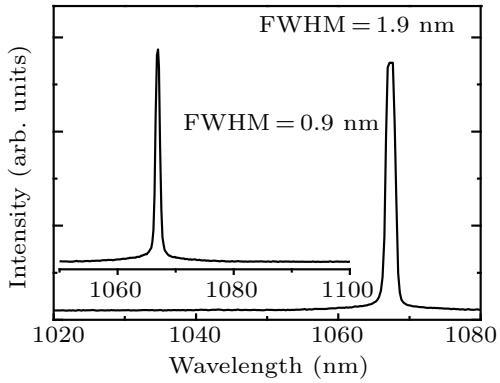


Fig. 6. Laser spectra of SLM and multi-mode Nd:KGdW laser.

4. Conclusion and perspectives

In this paper, we report a CW 1067-nm Nd:KGdW SLM laser by the double FP etalons technique. The utilizing of the N_g cut in an 'athermal' direction dramatically lowers the thermal lens effect inside the laser crystal, which is very helpful in realizing the Nd:KGdW SLM laser. The highest SLM output power of 64.8 mW is obtained at incident pump power of 4.7 W, corresponding to an optical conversion efficiency of 1.3% and a slope efficiency of 1.7%. This unique 'athermal' direction will pave the way for KGdW crystal to have wider application fields.

References

[1] Barry J F, McCarron D J, Norrgard E B, Steinecker M H and DeMille D 2014 *Nature* **512** 286
[2] The LIGO Scientific Collaboration 2011 *Nat. Phys.* **7** 962
[3] Su X L, Tian C X, Deng X W, Li Q, Xie C D and Peng K C 2016 *Phys. Rev. Lett.* **117** 240503
[4] Dergachev A 2011 *Opt. Express* **19** 6797
[5] Wu J, Ju Y L, Dai T Y, Yao B Q and Wang Y Z 2017 *Opt. Express* **25** 27671
[6] Huang S, Wang Q, Zhang M, Chen C, Wang K, Gao M and Gao C 2020 *Chin. Phys. B* **29** 084204
[7] Zayhowski J J and Mooradian A 1989 *Opt. Lett.* **14** 24
[8] Chen Y J, Lin Y F, Huang J H, Gong X H, Luo Z D and Huang Y D 2019 *Opt. Express* **27** 26080
[9] Ju Y L, Liu W, Yao B Q, Dai T Y, Wu J, Yuan J H, Wang J, Duan X M and Wang Y Z 2015 *Chin. Opt. Lett.* **13** 111403
[10] Cong Z H, Liu Z J, Qin Z G, Zhang X Y, Wang S W, Rao H and Fu Q 2015 *Appl. Opt.* **54** 5143
[11] Li J, Yang S H, Zhao C M, Zhang H Y and Xie W 2010 *Opt. Express* **18** 12161
[12] Dou W, Pu S, Niu N, Qu D, Meng X, Zhao L and Zheng Q 2019 *Acta Phys. Sin.* **68** 054202 (in Chinese)
[13] Song B A, Zhao W J, Ren D M, Qu Y C, Zhang H Y, Qian L M and Hu X Y 2009 *Chin. Opt. Lett.* **7** 805
[14] Zhu L N, Gao C Q, Wang R, Gao M W, Zheng Y and Wang Z Y 2012 *Appl. Opt.* **51** 1616
[15] Dai T Y, Han L, Yao B Q, Ju Y L, Yu K K and Wang Y Z 2015 *Opt. Laser Technol.* **74** 20
[16] Demidovich A A, Shkadarevich A P, Danailov M B, Apai P, Gasmi T, Gribkovskii V P, Kuzmin A N, Ryabtsev G I and Batay L E 1998 *Appl. Phys. B* **67** 11
[17] Lubeigt W, Griffith M, Laycock L and Burns D 2009 *Opt. Express* **17** 12057
[18] Abdolvand A, Wilcox K G, Kalkandjiev T K and Rafailov E U 2010 *Opt. Express* **18** 2753
[19] Boulon G, Metrat G, Muhlstein N, Brenier A, Kokta M R, Kravchik L and Kalisky Y 2003 *Opt. Mater.* **24** 377
[20] Major A, Langford N, Graf T, Burns D and Ferguson A I 2002 *Opt. Lett.* **27** 1478
[21] Major A, Langford N, Graf T and Ferguson A I 2002 *Appl. Phys. B* **75** 467
[22] Major A, Aitchison J S, Smith P W E, Langford N and Ferguson A I 2005 *Opt. Lett.* **30** 421
[23] Loiko P A, Yumashev K V, Kuleshov N V and Pavlyuk A A 2012 *Appl. Phys. B* **106** 881
[24] Mochalov I V 1997 *Opt. Eng.* **36** 1660
[25] Filippov V V, Kuleshov N V and Bodnar I T 2007 *Appl. Phys. B* **87** 611
[26] Biswal S, O'Connor S P and Bowman S R 2005 *Appl. Opt.* **44** 3093
[27] Yumashev K V, Savitski V G, Kuleshov N V, Pavlyuk A A, Molotkov D D and Protasenya A L 2007 *Appl. Phys. B* **89** 39