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High power Nd:YVO-KGW conical refraction laser

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ABSTRACT

We have demonstrated the highest conical refraction (CR) laser output power to date by placing a CR crystal inside of a diode-pumped Nd:YVO laser cavity. The CR crystal did not have a significant influence on laser output power as well as efficiency. The CR laser produced the maximum output power of 3.68 W with the slope efficiency of 42 % and optical-to-optical efficiency of 34 %. Therefore, this approach could be an attractive pathway for further power scaling of the CR lasers.

Keywords: Conical refraction, solid-state laser, diode-pumped laser, Nd-doped laser crystals

1. INTRODUCTION

Conical refraction (CR) is a well-known phenomenon that happens when light propagates along one of the optical axes of a biaxial crystal. As it is shown in Fig. 1, in case of an input beam with Gaussian intensity distribution, CR transforms it into a pair of bright concentric rings separated by a dark Poggendorff ring.

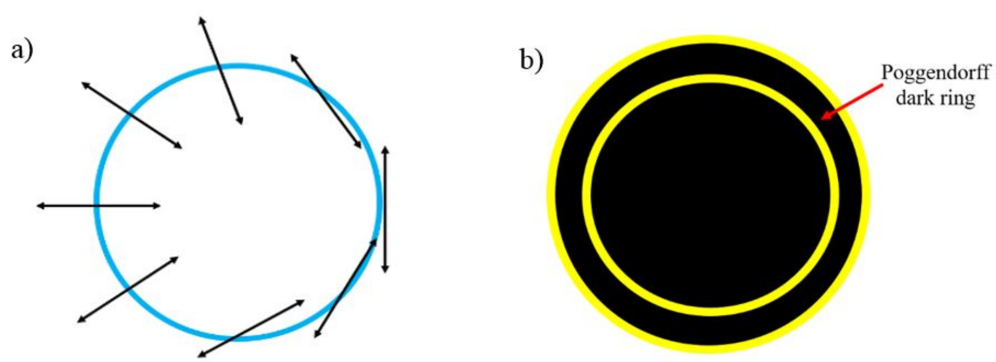

Figure 1. Schematic diagram of the a) polarization along the CR ring pattern and b) Poggendorff dark ring.

In recent years CR has been actively studied due to the potential applications in the fields of optical trapping, free space communication, super-resolution microscopy, cryptography, polarization demultiplexing and multiplexing, polarimetry and mode conversion [1-4]. Currently the most popular way to produce a CR laser output is to combine the CR and optical gain properties of a biaxial Nd:KGW laser crystal [5-10]. However, the output power of the CR Nd:KGW lasers demonstrated to date was limited by moderate thermal conductivity of this crystal [11-14]. To overcome this problem we have demonstrated a passive diode-pumped CR laser using a cascade of an active laser gain medium and a passive CR medium inside of a single optical cavity.

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$Nd:YVO_4$ (Nd:YVO) is one of the most popular laser host crystals because of its large stimulated emission cross-section, high absorption coefficient and wide absorption bandwidth at pump wavelength around 810 nm, high laser induced damage threshold, and high slope efficiency. Diode-pumped $Nd:YVO_4$ lasers have been demonstrated with multi-watt output and high efficiency in the continuous-wave and pulsed regimes [15-21]. Owing to the natural birefringence and strongly polarized laser radiation, they are a popular choice for efficient process of frequency conversion [22,23] and are widely used to pump Ti:sapphire and Alexandrite lasers [24-27]. The optical and physical properties of Nd:YVO crystal are listed in Table 1 along with the crystals of Nd:KGW and Nd:YAG for comparison. The emission spectrum of Nd:YVO is displayed in Fig. 2.

Table 1. Properties of the Nd:YVO, Nd:YAG and Nd:KGW crystals.

Laser crystal type	**Nd:YVO4**	**Nd:YAG**	**Nd:KGW**
Lasing λ nm	914, 1064, 1342	946, 1064 1319	911, 1067.2 1351
Emission cross section, X $10^{-19}cm^2$	**25** @ 1064nm	2.8 @1064nm	4.3 @1067.2 nm
Fluorescence lifetime[μs] @doping	90@1%	230@1%	110@3%
Gain bandwidth [nm]	0.96 @1064nm	0.6 @1064nm	2.73
Pump λ nm	808.5, 910	807.5	811, 910
Absorption coefficient [cm^{-1}] @ doping 1%	31.4 @810 nm (π, e)	7.1 @810 nm	4.5
Thermal conductivity [W/mK]	**|| c:5.23** **⊥ c: 5.10**	14	2.8[100] 2.2[010] 3.5[001]

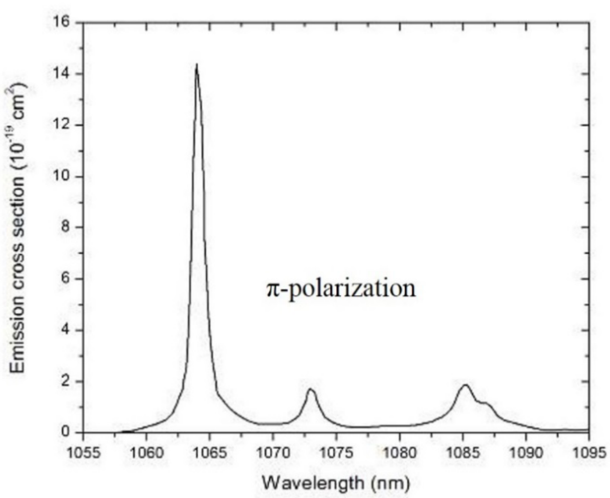

Figure 2. Emission spectrum of $Nd:YVO_4$ around the main transition at 1064 nm [28].

As can be seen from Table 1, Nd:YVO has higher thermal conductivity and stimulated emission cross-section both of which can help to produce high output power level from a laser. Taking into account that 1064 nm is not absorbed by the KGW crystals, this encouraged us to use Nd:YVO as a laser gain medium for passive CR laser in our experiment.

2. EXPERIMENTAL SETUP

The passive CR laser used a Nd:YVO crystal as a laser gain medium. The 20 mm-long 1.5 at.% Nd:YVO crystal was wrapped with indium foil and water cooled at the flow rate of 1 liter/minute on the top and bottom surfaces in a copper holder at 16 °C. Both surfaces of the crystal were anti-reflection coated at the laser and pump wavelengths. The crystal was pumped by a fiber-coupled diode laser with a fiber core diameter of 110 μm and a numerical aperture of 0.22. Diode pumping used ~914 nm wavelength which was previously shown to reduce the effect of thermal lensing [29,30] and increase the laser efficiency [31-36].

One arm of the standard z-cavity shown in Fig. 3 contained the laser crystal (Nd:YVO) and the opposite arm contained the CR crystal (KGW) close to an output coupler. The output coupler had 5% transmission in order to obtain the highest output power and optical efficiency. Cavity design took into account the effect of thermal lensing [37]. The CR crystal was an 18 mm-long anti-reflection coated KGW crystal which was cut along its optical axis. KGW crystals are well-known for the CR effect [38-42], have good optical quality [11] and are typically used as host for Nd- and Yb-ion lasers [43-53]. A photograph of the developed laser is shown in Fig. 4.

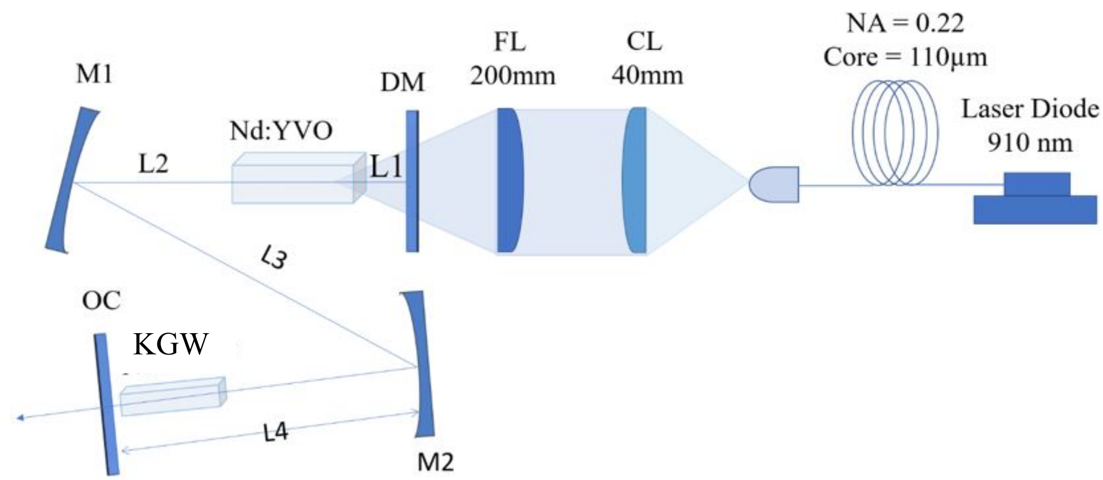

Figure 3. Laser cavity setup of the experimental CR laser. L1, L2, L3 and L4 distances are 24 mm, 398 mm, 370 mm and 174 mm, respectively. M1 and M2 are concave mirrors with r = 500 mm and r = 400mm, respectively. OC is the output coupler and DM is the dichroic pump mirror.

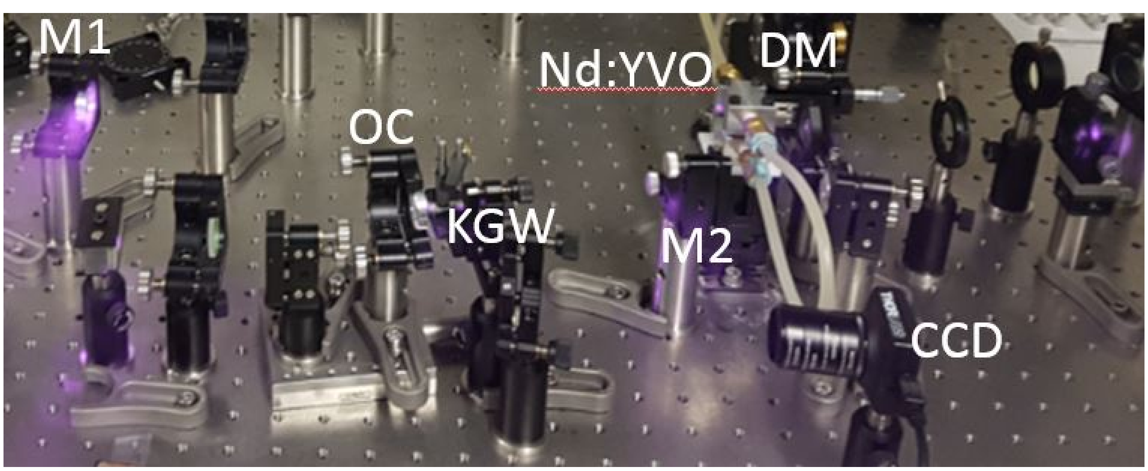

Figure 4. Laser setup on optical table.

The laser beam diameter was around 550 µm (200 µm) at the entrance of the Nd:YVO (KGW) crystal. The output beam (at the OC plane) was imaged onto a CCD camera using a single lens with 125 mm of focal length. Since the theoretical CR ring radius was 306 µm for our crystal, its ratio with the input beam size ρ_0 was 1.53. Using a red He-Ne laser the KGW crystal was aligned so that the cavity laser beam could propagate parallel to its optical axis.

3. RESULTS AND DISCUSSIONS

The maximum absorbed pump power by the Nd:YVO crystal was 10.8 W for the incident pump power of 31.2 W. The laser produced a CR output beam when the KGW crystal was properly oriented. In the CR regime the maximum output power of 3.68 W was produced. Figure 5 illustrates the output power vs the absorbed pump power. The slope efficiency from a linear fit was 42.3% and the optical-to-optical efficiency was 34.1% with respect to the absorbed pump power. To the best of our knowledge, this is the highest CR laser output power demonstrated to date and further power scaling is possible. Previously, up to 3.3 W were generated from the Nd:KGW CR laser although the beam did not display a CR pattern [6]. Figure 6 displays the optical spectrum of the generated CR laser radiation.

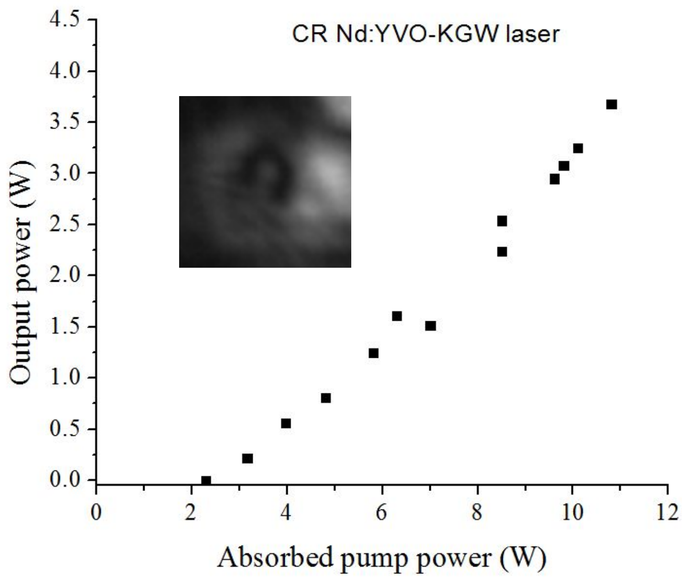

Figure 5. Output power of the CR Nd:YVO-KGW laser. Inset: CR beam intensity profile.

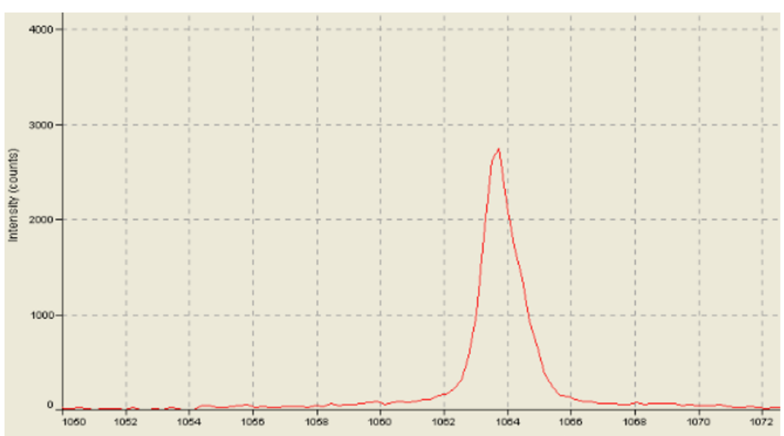

Figure 6. CR laser spectrum.

The presented results are preliminary. The observed ring shaped profile of the laser radiation is not clear because the ρ_0 is 1.53. For a clearly resolved double ring CR pattern with a dark Poggendorff ring one should satisfy the condition of the ρ_0>>1 [1]. Nonetheless, we believe that the observed pattern in our experiments can be explained by the conical refraction in the KGW crystal. Further experiments devoted to the accurate characterization of the CR nature of the produced radiation as well as theoretical modeling are in progress.

4. CONCLUSIONS

A proof-of-principle experiment to produce a CR radiation from a laser with the separate gain and CR media was carried out. The laser used a Nd:YVO crystal as a gain medium and a KGW crystal as a CR medium. The laser was diode-pumped and produced up to 3.68 W of output power at 1064 nm. The initial results indicate that the laser mode focusing conditions should be more tight in order to observe a well behaved CR pattern. At the same time, the proposed approach offers an easy way of achieving this along with the power scaling capabilities.

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