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# Diode-pumped Yb:CALGO laser with conical refraction output

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## ABSTRACT

A high power conical refraction (CR) laser was demonstrated based on Yb:CALGO laser crystal with a separate intracavity CR element. The CR laser delivered the maximum output power of 6.25 W at 25 W of incident pump power which is the highest output power for the CR lasers to date. The separation of the CR element from the laser gain medium reduced the complexity of laser pumping. The generated CR laser beam exhibited excellent quality with well-resolved concentric rings and the Poggendorff dark ring.

**Keywords:** Conical refraction, Yb-ion lasers, diode-pumped lasers.

## 1. INTRODUCTION

The generation of CR laser beam has recently attracted a lot of attention due to its potential applications for microscopy, optical trapping, communication, etc. [1]. In a uniaxial crystal with two principal refractive indices, the passing of a light beam through the crystal shows birefringence, i.e. it yields two rays called ordinary ray and extraordinary ray. The extraordinary ray lies with an angle with respect to the ordinary ray if the input beam is not propagating along the optical axis. In a biaxial crystal with three principal refractive indices and two optical axes, light propagation along the optical axes is a bit different from the uniaxial crystal. In a biaxial crystal, when light enters along the optical axis, one can observe a hollow cylinder in the output with annular intensity profile after the beam propagate conically through the crystal [1, 2]. Using aragonite and sunlight, Lloyd observed the transformation of the double refraction into CR light when the optical axis of the crystal was aligned with the incident beam [3]. Although Lloyd observed the CR phenomenon, but it was Poggendorf who demonstrated the first CR beam with excellent quality, i.e. the light rings of the CR beam were separated by a dark ring [4]. In 1941 Raman published his works [5-7] based on naphthalene crystals which are biaxial crystals with 10 times larger birefringence when compared to aragonite. In his works, he observed the Poggendorf dark ring between the two bright CR rings. In addition to that, he also recorded the variation in the intensity of the CR ring along the beam propagation path. He found that in the far-field the CR beam with Poggendorff dark ring between the two bright CR rings collapsed into a bright spot which is known as Raman spot [5-7].

The theory of the formation of the CR laser light and its properties can be understood from previous works [8-13]. In some of the previous reports [14-18], the laser gain medium also worked as a CR element (CRE). It complicates the understanding of the effect of the CR on the Gaussian laser mode. Recently, a new set up for CR laser was proposed where the CRE was kept separate from the laser crystal [19,20]. Keeping the CRE separate from the laser crystal does not only allow the power scaling but it also allows for laser adjustment to achieve better conditions of CR. Also, in this separate arrangement, the laser crystal properties are independent of the CR crystal properties.

Yb-ion lasers [21-23] are very popular because of their simple electronic configuration,  $^2F_{7/2}$  - the ground manifold and  $^2F_{5/2}$  - the upper manifold. As Yb-ion lasers do not have multiple higher levels, the effects such as up-conversion, concentration quenching, excited-state absorption are absent. Also, since the quantum defect (the difference between the pump and laser photon energies) is low this makes Yb-ion crystals attractive for high power laser operation [24-31]. Considering these important characteristics, Yb-ion lasers are becoming reliable in applications such as micromachining [32], optical communication [33], multiphoton microscopy [34-39] and nonlinear optics [40-43]. There are different types of Yb laser crystals available but Yb:CALGO is the most popular one because of its high thermal conductivity (6.5 W/m/K) with a 50 nm broad emission spectrum which makes it suitable for high power laser operation [44-55].

In this work, a multi-watt power scalable CR laser was investigated by using Yb:CALGO as the laser host and a separate intracavity CR element. An output power of 6.25 W was obtained for 25 W of incident pump power. We also investigated the beam evolution in the Lloyd image plane. We were able to generate a high quality CR laser beam with clear Poggendorff dark ring.

## 2. EXPERIMENTAL SETUP

A 5 mm-long Yb:CALGO crystal (*a*-cut, 2 at. %) was used in a five-mirror cavity configuration. Both input surfaces of the crystal had antireflection coating for pump and laser wavelengths. The cavity is shown in figure 1.

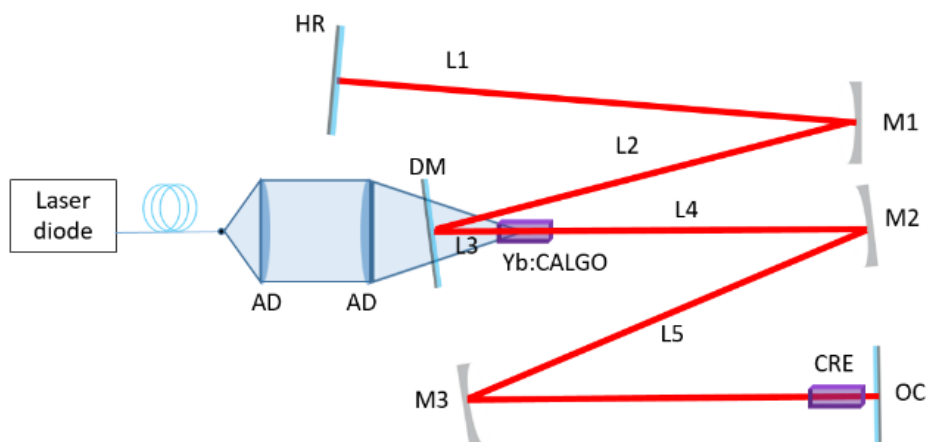


Fig. 1. Schematic of the laser cavity.  $M1 = -300$  mm,  $M2 = -250$  mm,  $M3 = -150$  mm, OC - output coupler, HR - highly reflective mirror, CRE - CR element.

The fiber-coupled laser diode delivered an unpolarized laser beam at 979 nm (N.A. = 0.22, fiber core diameter = 105  $\mu\text{m}$ ) and was imaged into a spot size diameter of 157  $\mu\text{m}$  in the laser crystal by using two achromatic doublet lenses. The laser cavity was optimized for the non-CR regime of operation (i.e. without a CR crystal in the cavity) by compensating for the thermal effect and optimizing the mode matching between the cavity mode and the pump beam. The maximum absorbed pump power under non-lasing condition was 13.22 W at an incident pump power of 25 W. The highest output power was 7.47 W at 25 W of incident pump power with 10% OC (output coupler).

After characterizing the laser in the continuous-wave (CW) regime, an 18 mm-long KGW crystal cut along its optical axis (the CR crystal) was placed between the focusing mirror M3 and the output coupler to observe CR laser radiation. The KGW crystal was also used in the previous experiments as a CRE [14-20,56-58]. The reason for the popularity of the KGW is the strong anisotropy in its optical and physical properties [59-60] as well as high optical quality. The latter also made it a popular gain medium for diode-pumped lasers in the CW and pulsed regimes [61-66]. The radius of curvature (ROC) of the focusing mirror M3 has a strong effect on the quality of the generated CR beam and the

details have been discussed in Ref. 19. Although increasing the ROC of M3 gives slightly higher output power, the pattern of the CR beam loses its double-ring structure. So, the lower ROC of M3 is a good choice considering the good CR beam quality with decent output power [19]. In our case, we chose  $M3 = -150$  mm which yielded a very high quality CR beam with 6.25 W of output power at 25 W of incident pump power.

### 3. RESULTS AND DISCUSSION

To generate a CR output beam, the optical axis of the CRE and the laser mode axis should be in parallel with each other. So, the alignment of the CRE was the most challenging part of the experiment. In the initial stage of the alignment, negligible output power indicated a large misalignment between the optical axis of the CRE and the laser mode axis. Further adjustment of the CR crystal resulted in a doubly refracted laser output with increased output power. At this stage, we needed to align the CR crystal together with the output coupler to obtain the CR pattern. We believe that a nice CR beam with a dark Poggendorff ring was obtained for perfect parallel orientation of the CR crystal along the cavity axis. The output beam was observed with a 60 mm imaging lens and a CCD camera.

The CR laser delivered a maximum output power of 6.25 W at 25 W of incident pump power by using a 10% output coupler. Using the lens and CCD camera, we recorded the evolution of CR beam intensity pattern after the output coupler. The position of the image plane was 1-3 mm away from the OC. As we got away from the Lloyd image plane along the beam propagation axis, the distinguishing features of the beam became faded and finally far away from the image plane we observed the Raman spot. The beam evolution is shown in figures 2(a)-(f). Another unique property of the CR laser beam is the polarization state distribution along with the CR pattern where every two diametrically opposite points have orthogonal polarization. The polarization state distribution along the CR beam was examined by using a polarizing beam splitter and indicated in figure 2(f).

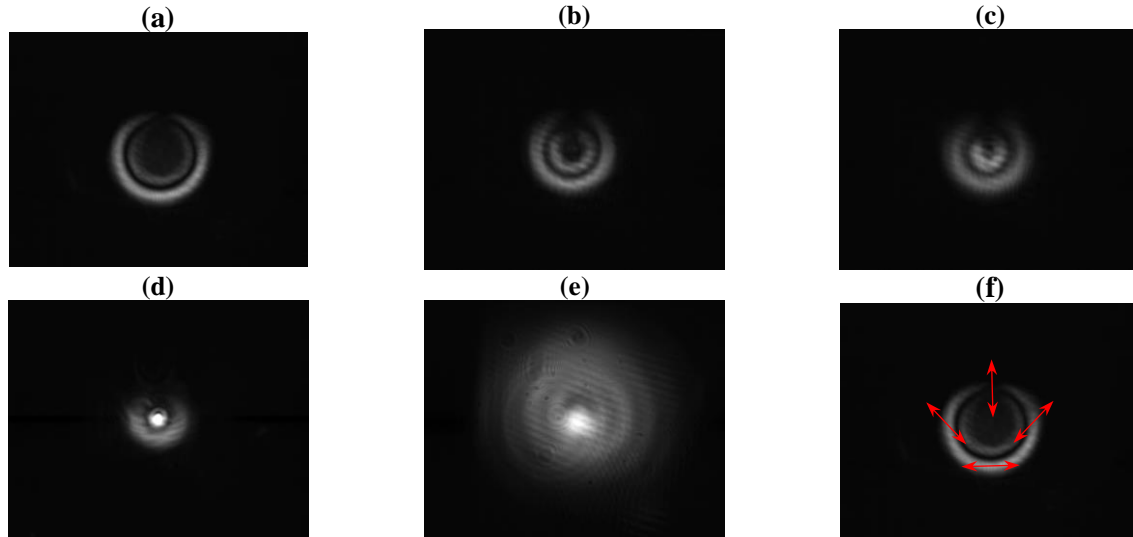


Fig. 2. The CR laser beam at the Lloyd image plane and its free-space evolution for the CRE with a horizontal orientation of its  $N_m$ -axis. It is mention-worthy that  $z$  is measured from the front surface of the OC: (a)  $z = 6.7$  mm, (b) 26.4 mm, (d) 41.7 mm, (e) 73.64 mm, (g) is  $z = 300$  mm which is far field view of the beam. (f) Local polarization states determined by a polarizer.

An important parameter that determines the quality of the CR output beam is the dimensionless parameter  $\rho_0$ , defined as the ratio of the radius of the CR beam to the input beam radius  $\rho_0 = R_o/w_o$  [1]. To have a clear CR beam with distinguishing Poggendorff dark ring, the recommended value is  $\rho_0 \gg 1$ . In our case,  $\rho_0$  was approximately 4 owing to the choice of small ROC of the focusing mirror M3.

To compare the performance of the CR laser against an equivalent non-CR laser (i.e. a typical laser with a Gaussian beam intensity profile), the CRE was replaced by a 20 mm-long AR-coated  $N_g$ -cut (non-CR) KGW crystal in the cavity. With a 10% output coupler, the maximum output power obtained with the undoped non-CR KGW crystal was 7.21 W at 25 W of pump power. In figure 3 the comparison of the output power among the CW, non-CR laser with the undoped KGW and the CR laser is given with respect to the corresponding input pump power.

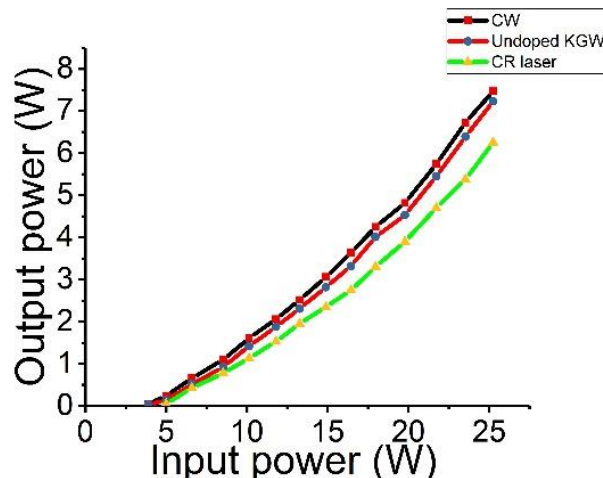


Fig. 3. The output powers vs. the incident pump power for the free-running CW, non-CR and CR lasers.

#### 4. CONCLUSION

In conclusion, a high power Yb:CALGO laser with a well-characterized CR beam based on a separate intracavity CR element was demonstrated. The power scalability of our laser was facilitated by the separation of the laser host and CR element. Because of this approach the CR beam properties became more independent from the lasing properties of the laser host (e.g. wavelength) and the cavity design parameters (e.g. pump spot size). The laser delivered a maximum output power of 6.25 W at 25 W of incident pump power. In addition to that, the beam evolution pattern was also observed. At the Lloyd image plane a clear CR beam with two concentric rings separated by the Poggendorff dark ring was obtained which in the far-field became a spot known as Raman. Future experiments will focus on further power scaling including the use of popular Nd-ion laser crystals [67-70] as well as continuous or discrete wavelength tunability [71-75] of the produced CR radiation.

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