Diode Pumped Laser Action and Self-Frequency Doubling in Nd^{3+}:YCOB

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ABSTRACT

Development of the oxyborate Nd^{3+}:YCOB has brought about the realization of single crystal elements under diode pumped operation for compact simple, solid state lasers producing visible laser emission. Efficient laser action and self-frequency doubling (SFD) has been obtained for both Ti:Sapphire and diode pumped operations. Comparable results were obtained for a hemispherical linear cavity with a 2% output coupler for fundamental operation. The fundamental output power of the Nd:YCOB under Ti:Sapphire pumping was in excess of 400 mW with a slope efficiency of 44% with ~ 1 W absorbed. Utilizing high brightness laser diodes, over 350 mW of fundamental output power has been obtained with a slope efficiency of 51% for similar absorbed powers. Efficient SFD operation was demonstrated in both pumping modes with no output coupling at the fundamental wavelength and high transmission of the second harmonic using a 5% doped Nd:YCOB crystal. Output powers of ~ 60 mW at 530 nm were obtained with both Ti:Sapphire and laser diode pumping.

Keywords: Self-frequency doubling, Nd^{3+}:YCOB, diode-pumping

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1. INTRODUCTION

There is much interest in the development of new Nd^{3+} doped laser crystals that possess nonlinear optical properties [1-6]. Self-frequency doubled (SFD) lasers are an attractive alternative to conventional intra-cavity frequency doubling with a separate nonlinear crystal, such as KTP. These new crystals have the advantage of combining the active laser medium and the nonlinear frequency conversion medium into a single element. A SFD laser incorporates lower reflection, absorption and scattering losses and leads to a simpler and more robust resonator design. With the addition of diode-pumping, SFD lasers provide a new type of compact high-power visible laser light source. Self frequency doubling was first demonstrated in $Tm:LiNbO_3$ [7] and then later in $MgO:LiNbO_3$ [1]. The latter met limited success because of its poor optical quality and the occurrence of photorefractive damage in the crystal [2]. SFD has also been observed in NYAB ($Nd:YAl_3(BO_3)_4$), but this material suffers from self-absorption at 530 nm [3,6] and is grown by a high-temperature flux method that often gives rise to crystals with poor optical quality and of small size [3].

Our interest in SFD lasers is driven by developments in a new class of laser host materials, the oxyborates [8,9]. These materials appear to have ideal properties for SFD action. Initial development of the oxyborates with SFD operation under Ti:Sapphire and diode-pumping was recently reported in both GdCOB [10-11] and YCOB [12].

2. YCOB CRYSTAL PARAMETERS

Nd:YCOB is an attractive material for SFD because it has demonstrated high optical gain at 1060 nm, a high nonlinear coefficient (~1 pm/V) [13], a high damage threshold (~1 GW/cm^2) [14], and the ability to be fabricated as large laser crystals possessing good optical quality. Moreover, it's principal absorption bands overlap well with the emission of high-power, near infrared-red, laser diodes. The oxyborates also offer advantages for harmonic generation [13,14] in that they are non-hygroscopic and can be grown with large apertures. In a separate study, we have found that both Yb and Nd doped YCOB can be used as an efficient second harmonic generation crystal [15].

We have successfully developed the Czochralski growth process to produce large (3" diameter x 8" long) high quality, single Nd:YCOB crystals. YCOB has a monoclinic crystal structure with the space group Cm (point group m) [9] and therefore the crystallographic axes are non-orthogonal. The lattice parameters of the unit cell are a = 8.046 Å, b = 15.959 Å and c = 3.517 Å with the angle β = 101.19° [13]. We have previously defined the X, Y, and Z, optical indicatrix axes relative to the crystallographic axes and planes by adopting the traditional refractive index convention $n_x < n_y < n_z$ [16,17]. The orientation of the optical indicatrix axes relative to the crystallographic axes and the crystal orientation for optimum SFD laser action in Nd:YCOB are shown in Fig. 1a and 1b respectively.

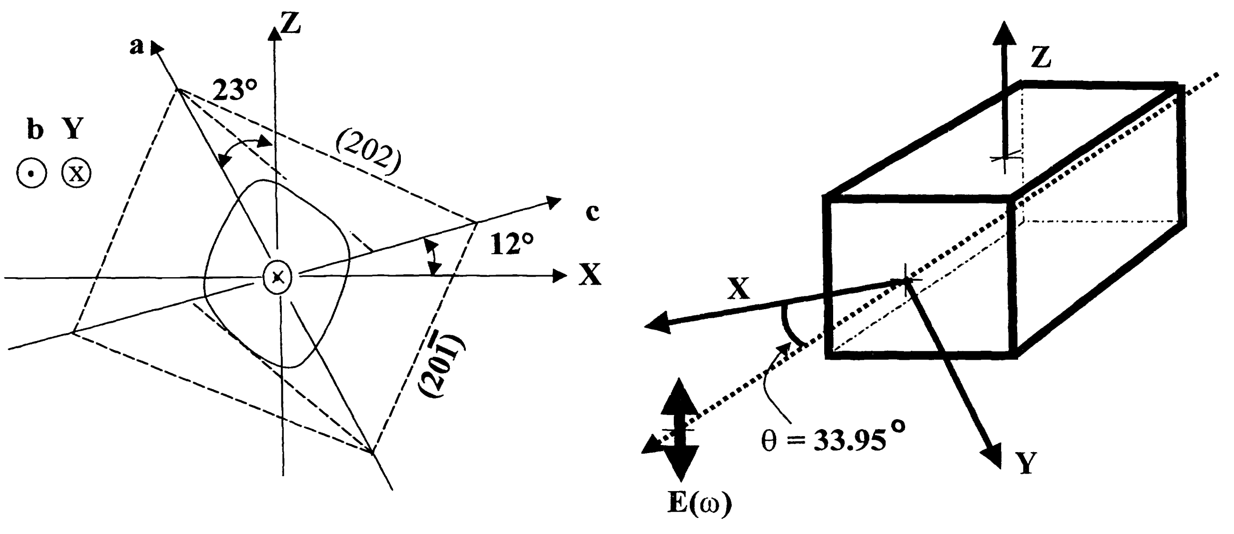
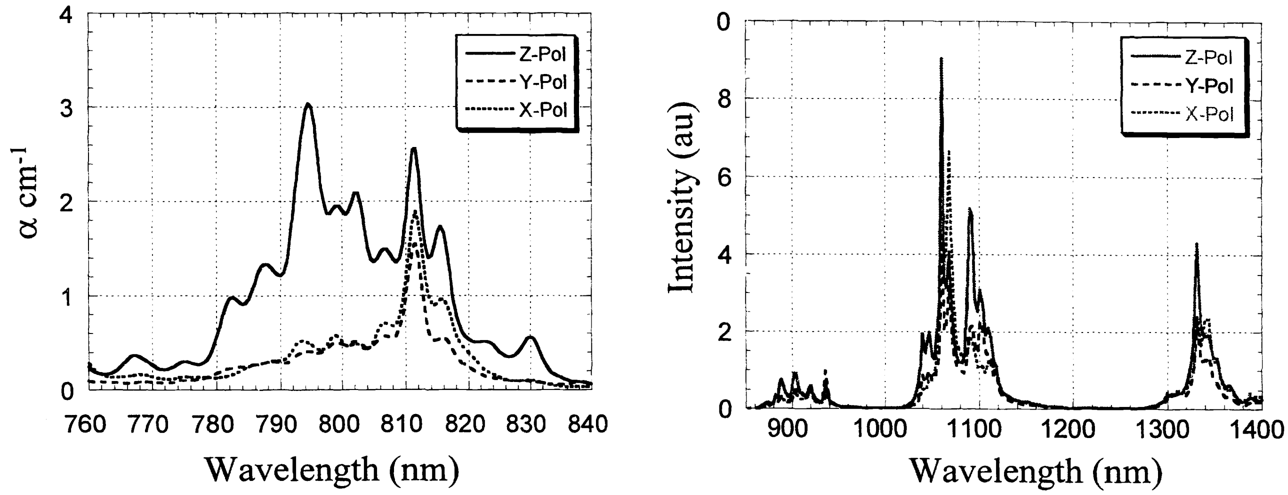


Figure 1 (a) Orientation of the optical indicatrix axes relative to the crystallographic axes for Nd:YCOB. (b) Crystal orientation for optimum SFD laser action in Nd:YCOB

The polarized absorption and emission spectra of 5% Nd:YCOB for light polarized parallel to the X, Y, and Z optical axes are shown in Fig. 2a and Fig. 2b respectively. These figures show that the strongest absorption and emission occurs for light polarized parallel to the Z-axis. There are three main emission lines in Nd:YCOB at 936 nm, 1060 nm, and 1331 nm. When these three laser wavelengths are self frequency doubled they produce blue, green and red respectively.



(a) (b)

Figure 2 (a) absorption spectrum and (b) emission spectrum for 5% Nd:YCOB as a function of polarization relative to X,Y and Z crystallographic axes.

3. TI:SAPPHIRE PUMPED FUNDAMENTAL LASER OPERATION

The initial laser experiments were performed with the intent of investigating the potential of this material as a laser medium. A simple hemispherical laser system pumped by a tunable cw Ti:Sapphire laser was constructed, Fig. 3, shows the cavity layout, consisting of a 5-meter radius of curvature high reflector and a 10-cm radius of curvature output coupler. The uncoated 5 mm x 5 mm x 13 mm long 2% Nd:YCOB crystal was placed next to the high reflector.

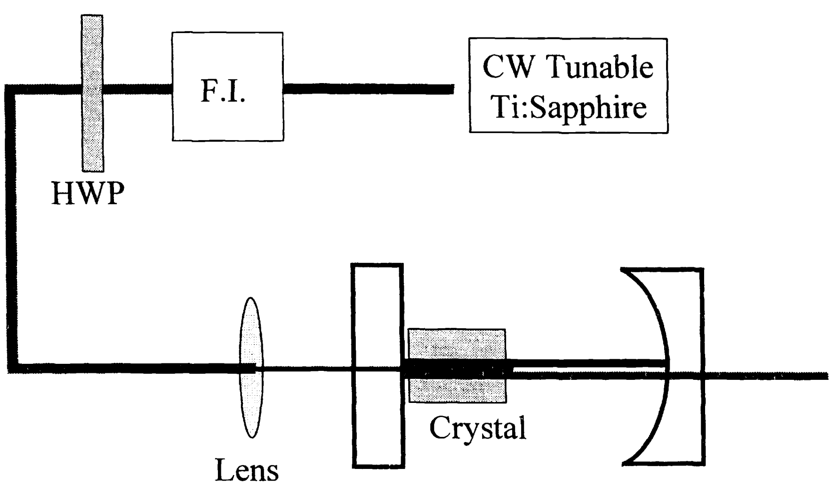


Figure 3: Experimental cavity design. F.I. – faraday isolator, HWP – Half-wave plate, Lens – 8.8 cm PL/CX lens, HR – 5 m ROC mirror, Crystal – 2% Nd:YCOB, OC – 10 cm ROC output coupler.

The tunablility of the Ti:Sapphire laser allowed pumping on either the 792nm or 812 nm absorption line. The pump laser polarization was rotated for maximum absorption in the crystal and focused into the crystal with an 8.8-cm plano/convex lens. Fig. 4 shows the fundamental output power for two percent output coupling versus absorbed pump power. Slope efficiencies of 44% with output powers exceeding 400 mW for 1 Watt of absorbed pump power were obtained for 2% output coupling.

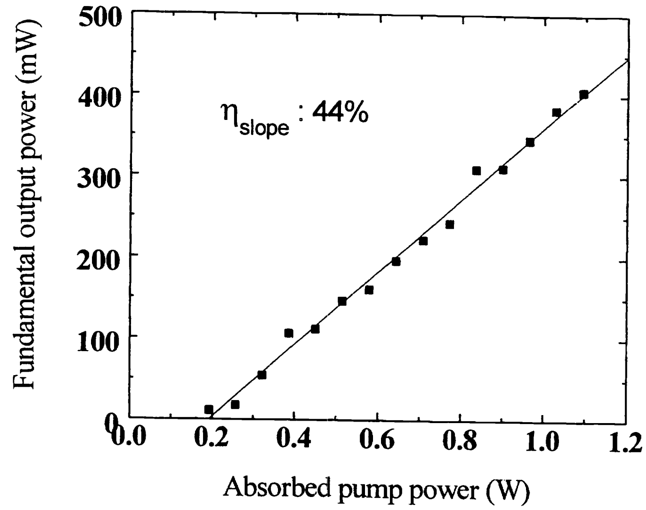


Figure 4: Fundamental Output Power vs. absorbed power.

4. TI:SAPPHIRE PUMPED SELF FREQUENCY DOUBLED OPERATION

Efficient self frequency doubling was demonstrated utilizing a 3 x 3 x 5 mm long, 5% Nd:YCOB crystal. Both crystal surfaces were coated with a triple band anti-reflection coating (Quality Thin Films TBAR) which had less than 1% reflection at 1060, 530 and 812 nm. The crystal absorbed approximately 80% of the pump light. The cavity design was identical to the linear cavity discussed above. To maximize the SFD output, the output coupler was highly reflecting at 1060 nm (R>99%) and highly transmitting (T>94%) at 530 nm. The SFD output was optimized by adjusting the angle and hence phase matching of the crystal and by varying the mode size in the crystal by changing the cavity length. The SFD power as a function of absorbed pump power is shown in Fig. 5. Nearly 60 mW of 530 nm laser light was obtained with 900 mW of Ti:Sapphire pump power absorbed in the crystal.

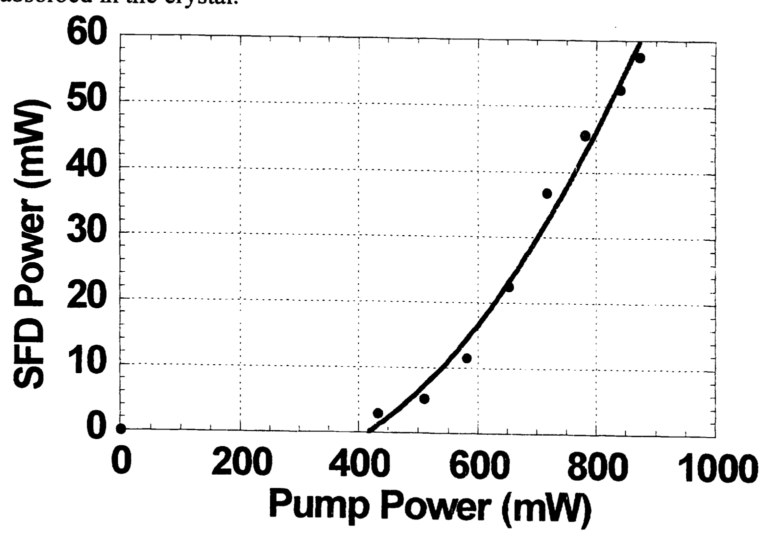


Figure 5: Self Frequency-doubled output power vs. absorbed Ti:Sapphire pump power.

The laser cavity length was optimized for high power SFD output. The laser threshold for SFD output was only 23 mW of power absorbed in the crystal. The reason for the sharp falloff of the green SFD power with a reduction of pump power in Fig 5 was believed to be due to a strong thermal lens inside the cavity rendering the cavity unstable. At lower pump powers (500 mW), the SFD power could be significantly increased with slight realignment of the 10 cm ROC mirror. The SFD output spectrum is shown in Fig. 6. No additional elements were inserted into the cavity to narrow the linewidth of the laser.

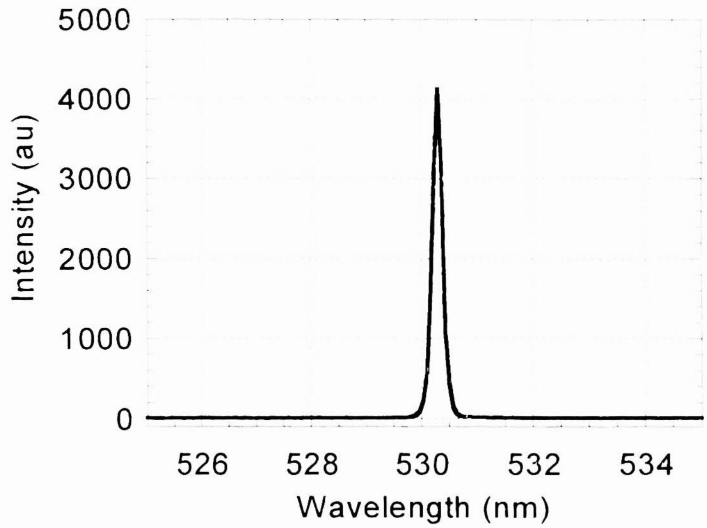


Figure 6: Self Frequency-doubled wavelength spectrum

5. DIODE PUMPED FUNDAMENTAL OPERATION

Diode-pumped experiments were performed with a simple laser resonator, similar to the Ti:Sapphire pumped cavity described above. The high brightness, AlGaAs laser diode (Polaroid POL-5100BW) had a maximum output power of 1.85 W from a 100 μm stripe and was centered at a wavelength of 812 nm. A 125 μm diameter fiber lens was utilized to collect the emission from the laser diode's fast axis and help equalize the divergence from the fast and slow axis. After the micro lens, a 50 mm focal length achromatic doublet lens was used to collect the diverging pump beam. After collimation, the pump beam is refocused with a 60 mm focal length Gradium™ plano /convex lens to a ~ 50 x 70 μm (FWHM) spot size, as measured with a scanning slit beam profiler (Photon Inc.).

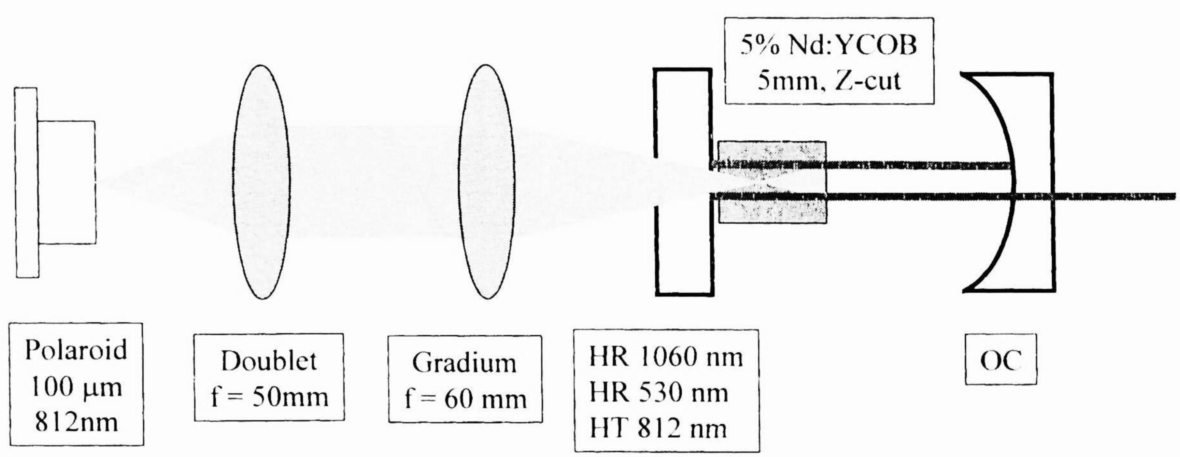


Figure 7 Diode pumped Experimental Setup

The hemispherical laser resonator shown in Fig. 7 consisted of a highly reflective rear mirror and a 10-cm radius of curvature output coupler. The 3x3x5 mm long, 5% Nd:YCOB crystal was placed next to the high reflector. The crystal was cut with the polished faces aligned at an angle of 33.95° to the X-axis. Both surfaces were coated with the same triple band anti-reflection coating described above. The crystal absorbed approximately 75% of the incident pump light at full current to the diode. The pump laser polarization was parallel to the Z-axis and was focused into the crystal through the rear mirror, which was 95% transparent at 812 nm. The fundamental (1060 nm) output power versus the absorbed pump power is shown in Fig. 8 for 1% and 2% transmission output coupling. The polarization of the laser output was parallel to the Z-axis. Output powers exceeding 340 mW for 900 mW of absorbed pump power were obtained with a slope efficiency of 51%.

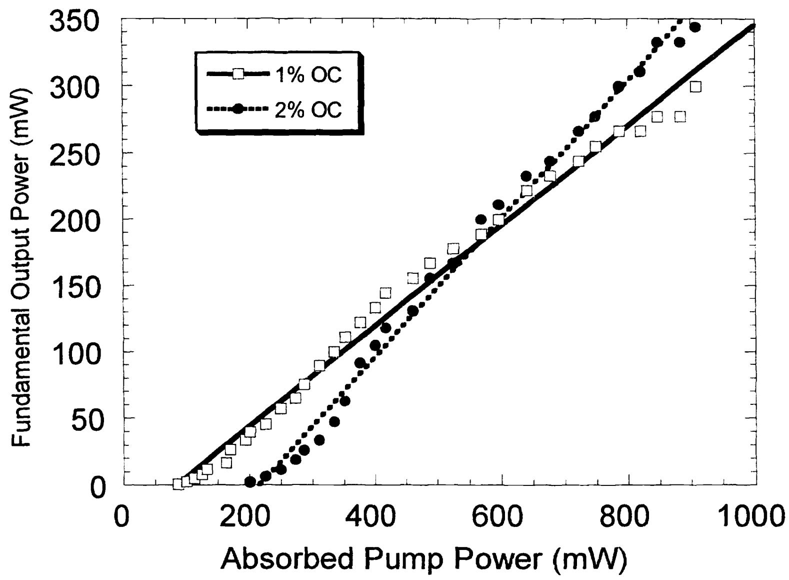


Figure 8 Fundamental output power as a function of absorbed diode pump power

6. DIODE PUMPED SELF-FREQUENCY DOUBLED OPERATION

Efficient diode-pumped self-frequency doubling was demonstrated utilizing the same crystal in the resonator design identical to that described above. To maximize the SFD output, the 10 cm ROC output coupler was, highly reflective at 1060 nm (R=99.82%) and highly transmissive (T>96%) at 530 nm. The SFD output was optimized by adjusting the angle and hence phases matching of the crystal, and by varying the mode size in the crystal by changing the cavity length. The SFD power as a function of absorbed diode pump power is shown in Fig. 9. Over 62 mW of 530 nm laser light was obtained with 900 mW of pump power absorbed in the crystal. At this power, the spatial mode profile of the SFD laser output as measured by a Spiricon LBA-100A was slightly multi-mode. The onset of SFD output occurred for only 100 mW of diode power absorbed in the crystal. The spectrum of the SFD output consisted of a single, narrow (<0.6 nm) line at 530.3 nm.

The intracavity fundamental (IR) power was estimated to be approximately 4.2 W by measuring the fundamental power leaking through the 10 cm ROC highly reflective mirror. The intracavity conversion efficiency is estimated to be over 1.5%. On the assumption that the intracavity mode cross section is similar to the pump beam area (3.5 x 10^{-5} cm^2), the intracavity power density was estimated to be approximately 120 kW/cm^2.

As with most intracavity frequency doubled lasers with many oscillating longitudinal modes, the SFD process in Nd:YCOB has large amplitude fluctuations due to longitudinal mode coupling through the sum-frequency generation process which strongly modulates the second harmonic light [18]. Other SFD crystals have seen between 3% and 6% peak-to-peak [19] amplitude fluctuations. The measured RMS noise in the present laser within a bandwidth of 5 Hz - 1 MHz was approximately 5%. This RMS noise fluctuation is a consequence not only of multi-longitudinal mode oscillations but also of coupled polarization modes [20] and feedback instabilities on the diode due to the absence of antireflection coatings on the pump optics. In these initial experiments no attempts were made to reduce the RMS noise of the SFD output.

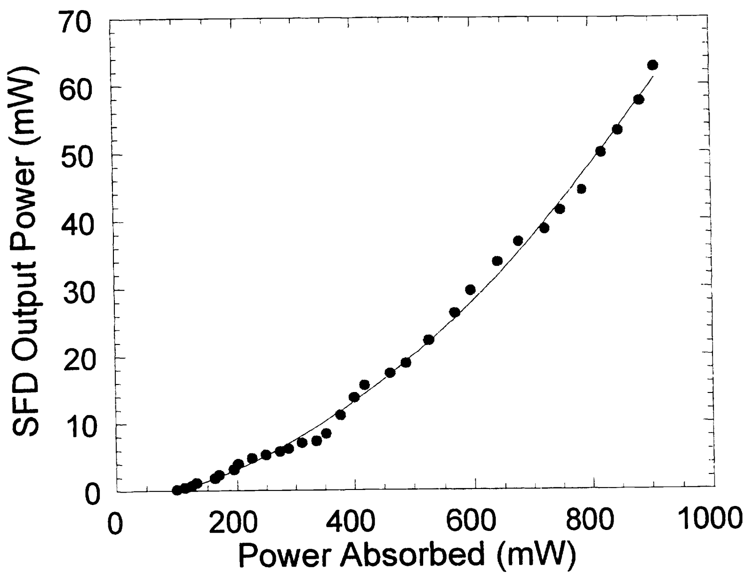


Figure 9 Self-frequency doubled output power as a function of absorbed diode pump power

7. SUMMARY

We have demonstrated the potential of the Oxyborate host Nd:YCOB as a new Self-Frequency doubled material. We have obtained high output powers and high slope efficiencies in both Fundamental and SFD operation utilizing both Ti:Sapphire and laser diode pumping. In summary, by generating over 62 mW of diode-pumped, green SFD laser light, we have shown that Nd:YCOB is a good candidate for a compact, diode-pumped, visible laser system. Detailed measurements of the thermo-mechanical properties of the YCOB crystalline host are essential to help determine the factors which could limit the scaling of the SFD output to higher powers.

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