L.8 : Generation of 100W green laser beam by intracavity doubling of diode-side-pumped Q-switched Nd:YAG laser

High-average-power laser emitting at 532 nm plays important role in various applications in industry, research and even in entertainment. These applications include processing of high reflectivity materials such as copper or silicon, pumping of high power dye or Ti: sapphire lasers, enacting a large scale laser show etc. Solid State Laser Division has designed an intra-cavity frequency doubling of acousto-optically Q-switched Nd:YAG laser under diode laser pumping using diffuse reflector based pump head generating more than 100W of green laser beam with high efficiency and stability. The laser consists of two pump heads (PH1 and PH2) to couple the diode laser beam to the Nd:YAG rod, a nonlinear crystal for intra-cavity frequency doubling, two orthogonally oriented acousto-optic modulators (to increase the hold-off capability) operating at 17 kHz repetition rate (QS1 and QS2) for repetitive Q-switching, a 90° quartz rotator for birefringence compensation and a resonator.

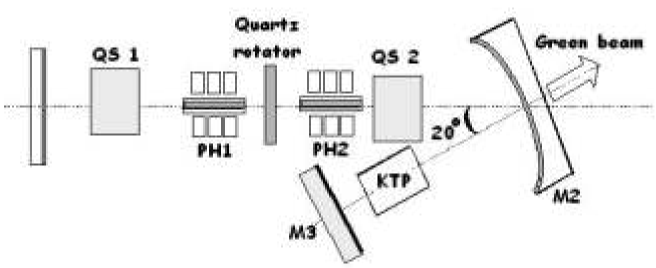

Fig.L.8.1: Schematic of the laser setup

The laser arrangement is shown schematically in Fig.L.8.1. Each laser head consists of a Nd:YAG rod (diameter: 5mm; length 100 mm, orientation [111]) with 0.6% (atomic) Nd^{3+} doping concentration, a cooling sleeve, a diffusive optical reflector and three diode array modules. The rod is surrounded by an anti-reflection coated cooling sleeve and placed at the centre of a three-slit symmetric cylindrical diffusive optical cavity. This cavity distributes the pump beam uniformly through the crystal rod, and minimizes the thermally related optical losses. The three slits (1.5 mm width) of the diffusive optical cavity allowed coupling of the emission of three linear diode arrays directly to the laser crystal rod.

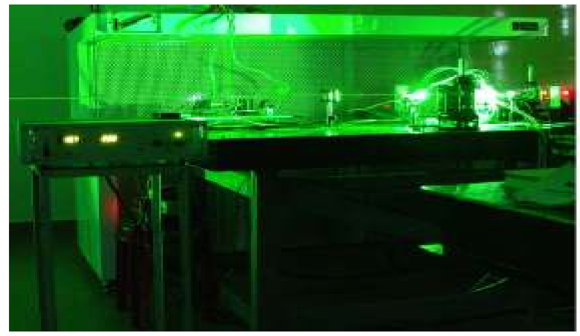

Fig.L.8.2. Photograph of the high power green laser.

For second harmonic generation (SHG), a 10 mm long KTP crystal cut for type-II phase matching at 80°C was used. The crystal was mounted in a temperature-controlled unit that held the crystal at 80°C to avoid gray tracking problems. The resonator was a simple three mirror V-shaped cavity designed to obtain both a large mode area at the gain medium and tight spot size at the KTP crystal. The rear mirror M1 was a plane mirror with high reflection coating at the fundamental wavelength at 1064 nm (R>99.7%). The other end mirror M3 was a plane mirror with dual wavelength high reflection coating at 1064 nm (R > 99.7%) and at 532 nm (R > 99.5%) in order to retro-reflect the backward generated green beam. The cavity was folded by a concave mirror M2 having radius of curvature of 250 mm. Mirror M2 was having high reflection coating at the fundamental wavelength (R > 99.7%) and high transmission coating (T > 95%) at the SHG wavelength to couple out the green beam. The pump head was placed between the two mirrors M1 and M2 and the KTP crystal was kept between the mirrors M2 and M3. A 90o quartz rotator was placed in between the two pump head for the compensation of the thermally induced birefringence in the laser rod. First the laser was operated in CW mode at the fundamental wavelength at 1064 nm by removing the AO modulators and the KTP crystal in a closed coupled linear cavity configuration. With an output coupling of 8% maximum 200 W of CW IR power was obtained corresponding to more than 34% optical to optical conversion efficiency.

At a total diode pumping power of 584 W, maximum 106 W of average green power at 532 nm was obtained corresponding to more than 18% optical to optical conversion efficiency. Fig.L.8.2 shows the picture of the laser in operation. It should be noted that more than 50% of the fundamental output power was converted to green beam.

The slope efficiency curve was highly linear without any sign of power rolling-off. However the heat load at the KTP crystal was very high because KTP has significant absorption at 532 nm. This shifts the phase matching direction significantly away from the resonator axis and the green power could not be scaled up further by increasing the pump power. Moreover, at this high power the formation of gray tracks and subsequently damage of the KTP crystal is highly probable. Hence efforts are currently in progress for simultaneous cooling arrangement for the KTP crystal.

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L.9 : Demonstration of > 3.4 mW laser at 266nm by intracavity doubling

Solid State Division has demonstrated an all solid-state Single Longitudinal Mode (SLM) UV laser at 266nm with more than 3.4mW output power by intracavity doubling of single frequency green laser at 532nm in a frequency locked slave ring cavity. Fig.L.9 shows the schematic of the set-up. The major parts of the design were the diode pumped single frequency pump laser at 532nm and the frequency locked slave ring cavity. Special design techniques were used to generate the required single frequency CW pump laser at 532nm with the highest ever-reported optical-to-optical conversion efficiency from 809nm pump laser to 532nm. Hansch-Couillaud frequency locking technique was used for frequency error signal generation and special home-made control electronics with SCAN/LOCK facility was used both for slave cavity fine-alignment and frequency locking.

The single frequency pump laser was based on a diode end pumped Nd:YVO_4/KTP laser along with an intracavity Brewster plate. Special design techniques were adopted to enhance the optical-to-optical conversion efficiency at 532nm in the CW single frequency operation with respect to the absorbed pump power at 809nm. This includes selection of a proper V-shaped cavity allowing larger focussing ratio in the NLO crystal, utilization of short absorption depth effect in the semi monolithic gain medium, active etalon effect in the gain medium with 66GHz FSR, a loss discriminating type of birefringent filter based on KTP/Brewster plate with 250GHz FSR and a gain discriminating type of birefringent filter based on a-cut Nd:YVO_4/KTP crystal with 250GHz FSR etc. These measures along with the gain aperture effect in the gain medium resulted in highly efficient single frequency laser at 532nm with more than 271mW of output power from an absorbed pump power of 934mW at 809nm. Accounting for the 86% transmission efficiency of the collection optics at 532nm, the estimated optical-to-optical conversion efficiency was 33.7%. The highest efficiency reported in single frequency laser at 532nm is 29.3% with only 55% useful output at 532nm, and is based on a linear cavity. The useful output was 86% in our design and was limited mainly by dielectric coating on the green output coupler. The single frequency operation was confirmed by analyzing the spectral output at 532nm using a scanning confocal FPI with a finesse of 200 and FSR of 1.5GHz (Coherent). The measured beam quality factor at 532nm was 1.07 using Mode-master from Coherent and was nearly circular in shape.

Intracavity doubling in a frequency locked slave ring cavity was used to generate SLM 266nm. Hansch-Couillaud scheme was used for the frequency locking of the slave cavity with the free running single frequency laser at 532nm. We used a Bow-Tie-Ring cavity geometry for the slave cavity, and also ensured proper mode matching and optimum impedance matching. A plane-plane input coupler (M4) with 2.1% transmission at 532nm resulted in impedance matching of the pump beam with the slave cavity. In order to generate frequency error signal with sufficient magnitude, the polarization of the incident beam was rotated by ~10^0 with respect to the polarization supported by the ring cavity with in intracavity Brewster cut SHG crystal by means of a Half Wave Plate (HWP) at 532nm. Since 100% mode-matching results is zero magnitude frequency error signal in an impedance matched cavity and maximum possible real enhancement factor (ratio of circulating pump power to the incident pump power at 532nm in this case), an optimum value of mode matching (lower than 100%) is necessary to optimize frequency error signal and the real enhancement factor. A beam transfer optics with 10X magnification resulted in an optimum mode matching of ~81.6%. Though the incident pump power was only ~200mW(on the ring cavity), the circulating pump power at 532nm was estimated to be ~7.9W resulting in a real enhancement factor of the cavity of ~39.5. The theoretically expected value of real enhancement factor based on the input coupling and the mode matching was ~38.8 for the same configuration and was found to be closely matching with the observed value within 2%.