L.3: Development of 160 W of single transverse mode Yb-doped CW fiber laser

High power CW fiber lasers are required mainly for materials processing and defence applications. Cladding pumped fiber lasers, which use double-clad fiber architecture and can produce single-mode laser output without requiring single mode diode pump sources are most widely used for generation of kW-level CW output powers. In view of this, there has been a growing interest in high power Yb-doped fiber lasers as a potential replacement for bulk solid state lasers in many applications. In addition, fiber lasers also provide inherent advantages in terms of higher efficiency, single-mode output, long life of maintenance free operation, no cooling requirement, and no risk of misalignment by means of intra-core fiber Bragg grating mirrors. Further, wide absorption band of Yb-doped fibers from ~800 to ~1064 nm and lasing wavelengths from ~974 to ~980 nm and ~1010 to ~1160 nm makes it a unique laser source for various applications. Higher output power from fiber lasers can be generated either from oscillator or using master oscillator power amplifier (MOPA) configurations. However, the output from single fiber or MOPA is mainly limited by thermal effects, nonlinearities and optical damage of fiber optic components. In view of multiple advantages of Yb-doped fiber lasers, it is of vital importance to study and develop such laser systems. Although, there has been a lot of worldwide effort to generate high power kW-class CW fiber lasers and make these lasers commercially available, it is critical to develop and understand physical aspects involved in development of such high power CW fiber laser systems in Indian context.

The experimental set up consists of a large mode area (LMA) Yb-doped double-clad active fiber with a core diameter of 20 µm, inner clad diameter of 400 µm, and outer clad diameter of 550 µm. Pump absorption for inner clad launching of the pump beam at 975 nm is 1.7 dB/m. Both the ends of the Yb-doped fiber were perpendicularly cleaved and the fiber was coiled on a metallic mandrel of appropriate diameter to remove heat load from the active fiber and to remove higher order modes.. A total of fourteen number of fiber pigtailed diodes of 30 W output power at 975 nm with pigtail fiber core diameter of 200 µm and 0.22 NA were selected to pump from both the ends of the Yb-doped fiber using 7:1 multimode pump combiners. Temperature of all the diodes was maintained at 25°C for the whole range of its operations using water cooled heat sinks for its mounting. Fiber pigtails of seven such diodes were fusion spliced individually with seven pump input ports of multimode pump combiner using Vytran GPX-3400 fusion splicing workstation. Maximum transmission of ~86% was achieved with optimized splice joints. A loss of 10% can be accounted for mismatch between fibers of diode pigtail and pump combiner fiber input ports along with pump combiner insertion loss from each input port. Output port of the pump combiner had a core diameter of 400 µm and an NA of 0.46. Two such diode pump modules were made (see fig.L.3.1) and used to pump from both ends of the Yb-doped double clad fiber using two fiber optic pump combiners. Pump beam from output port of each pump combiner was collimated using a 20 mm focal length lens and then it was imaged at the Yb-doped fiber ends using another 20 mm focal length lenses. Both the ends of the Yb-doped fiber were held in temperature-controlled metallic V-grooves to prevent possible thermal damage to the gain fiber coating by any over filled pump or signal power, or by the heat generated in the gain fiber due to non-radiative emission processes. A dichroic mirror with high transmission (HT) at 975 nm and high reflectivity (HR) of ~100% in broadband from 1040-1100 nm for normal incidence has been placed at one end of the Yb-doped double-clad fiber between the two lenses for signal feedback. This mirror along with the other cleaved end of the Yb-doped fiber providing 4% Fresnel reflection act as resonator mirrors. Another dichroic mirror with HT at 975 nm and HR in a broadband from 1040-1100 nm at 25° angle of incidence has been placed between the two lenses to take out the laser beam from resonator. Figure L.3.1 shows a schematic of the experimental set-up and Fig.L.3.2 shows a view of in-house developed 160 W Yb-doped CW fiber laser.

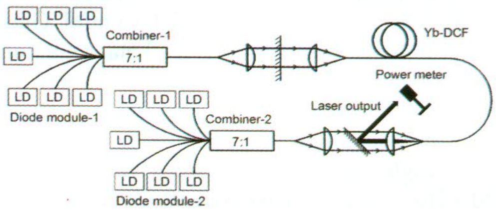

Fig. L.3.1: Schematic of the experimental set up

Fig. L.3.2: A table-top view of 160 W single transverse mode CW fiber laser.

Using this set up an output power of 165 W was achieved at the combined maximum input pump power of 316 W from both the ends with an optical-to-optical slope efficiency of 56.5%. Threshold pump power was measured to be 20 W. However, if we include pump coupling losses into account, optical-to-optical conversion efficiency improves to a value of 80.5%, which is close to the maximum reported figure of 83% for high power Yb-doped fiber lasers. Further experiments are underway to reduce pump coupling losses by using fiber Bragg gratings and making the fiber laser set-up with an all-fiber configuration. The output spectrum was peaked at 1079.7 nm with spread from 1064.1 nm to 1100.1 nm and FWHM linewidth of ~7 nm. Output beam profile was measured using a Spiricon make laser beam profiler and measured value of M^2 was found to be ~1.04, which shows a nearly diffraction-limited output laser beam. During development of high power fiber lasers, it was found that unwanted generation of relaxation oscillations near threshold and consequent generation of high peak power random self-pulsing with pulse duration of the order of a few nanoseconds damages fiber ends or any other fiber laser component, which is irreversible. So, it is extremely important to remove random self-pulsing, if it occurs, before anyone proceeds to generate high power output from Yb-doped fiber lasers. Fiber ends are also prone to damage by dust particles due to emission of high power from very small core size of the fiber and hence due to high power density at the fiber end faces, so it is also important to protect fiber ends by means of end caps.

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L.4: Indigenous development of laser glass

A program to indigenously develop Nd doped phosphate laser glass was funded by Board for Research in Nuclear Sciences (BRNS) with participation of Central Glass and Ceramic Research Institute (CGCRI) Kolkata, Raja Ramanna Centre for Advanced Technology (RRCAT), and Bhabha Atomic Research Centre (BARC) Mumbai, to overcome the problem of non-availability of good quality laser glass rods and discs for high energy, high power (HEHP) lasers. The LHG-8 (M/s Hoya, Japan) glass is currently used in the third generation HEHP lasers like National Ignition Facility (NIF), USA, and Laser Mega-Joule (LMJ), France. Under the MOU, CGCRI will supply 1000 kg of optical quality rectanguloid blocks to RRCAT. The slabs will be machined into laser rods and optically polished in RRCAT. Further, anti-reflection (AR) coating will be deposited at RRCAT on the end faces of the glass rods. The project has successfully passed the first stage of development in which following targets were achieved: a) Optimization of the process parameters for dry route of melting (mainly oxygen bubbling to control OH and Fe impurities); b) Indigenous development of highly pure raw materials like meta-phosphates of Al, Ba, K required for dry route of melting; c) Indigenous development of highly pure Nd_2O_3; d) Validation of Pt crucible and furnace design for glass melting; e) Indigenous sourcing of oxide dispersed Pt crucible; f) Civil, electrical and clean room (with controlled humidity) infrastructure for housing the machines; g) Procurement of annealing and fine annealing furnaces suitable for all the glass sizes; h) Generating infrastructure for transforming laser glass slabs into laser rods; and i) AR coatings of laser glass rods.

The work related to production of pre-cursor raw materials i.e. meta-phosphates of Al, Ba, and K with an impurity of less than 10 ppm (in the glass) of the transition metals like Fe, Cu, Cr and Ni was taken up with a vendor in Indore. Presently, highly pure meta-phosphate raw materials having a batch size 50 kg have been supplied to CGCRI with desired quality. The fluid dynamic calculations for the design and validation of crucible and stirrer had been taken up with IIT- Kanpur, and a five litre platinum crucible was fabricated with this design. The design of 15 litre crucible is ready and will be fabricated after the glass quality in terms of homogeneity is attained in the operational 5 litre crucible. Casting of molten glass using this crucible is shown in Fig.L.4.1. The trials for the turning of glass slabs into laser rods were done at RRCAT with the slabs supplied by CGCRI. The process of the turning of Glass slabs supplied by CGCRI is shown in Fig.L.4.2.The optical polishing of end faces has already been established in RRCAT. The Nd:Glass rods have been coated with a single layer sol-gel silica AR coating at RRCAT.

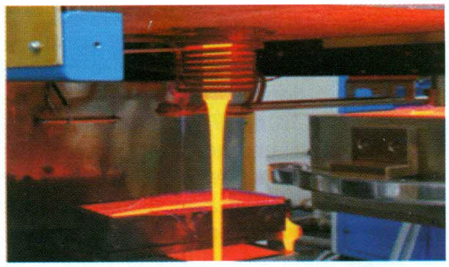

Fig.L.4.1: Casting of laser glass from5 liter bottom pouring furnace.

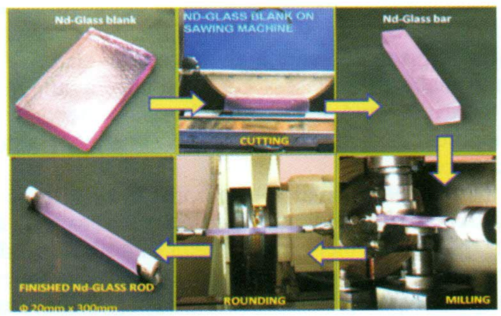

Fig.L.4..2: Optical machining of laser glass at RRCAT from slab to laser rod.

In the second stage of the program, the glass melted in 5 litre bottom pouring Pt crucible was cast, annealed and fine annealed. A slab of size 240 cm x 135 cm x 40 cm with Nd_2O_3 doping of ~ 3 wt% was received from CGCRI for the testing of its optical parameters. The slab surface was polished in the Optical Workshop of RRCAT. The slab was tested for optical homogeneity, birefringence, and for bubbles/inclusions. Presently this glass has total homogeneity (surface + bulk) of better than 6.10^{-5} as measured by the interferometry. This needs to be improved by a factor of two. The stimulated emission cross section (σ) and intensity dependent refractive index (n_2) values were measured using the method of amplification and the Boling's method respectively. These values were found to be comparable to the LHG-8 glass. Efforts are on to further improve the optical quality of the indigenous laser glass.

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