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Resonator to Laser Cavity Decoupling Interface for Chemical Oxygen Iodine Laser

A.K. Varshney[#,*], Rajeev Kr. Dohare[#], Gaurav Singhal[#], and Mainuddin[@]

[#]*DRDO-Laser Science and Technology Centre, Delhi - 110 054, India*
[@]*Department of Electronics and Communication Engineering, Jamia Millia Islamia, New Delhi - 110 025, India*
[*]*E-mail: anujkumarvarshneya@lastec.drdo.in*

ABSTRACT

In the present work, the conventional chemical oxygen iodine laser (COIL) source has been technologically upgraded and successfully tested after implementation of decoupling interface between laser cavity and resonator. In the technique, anti-reflection coated fused silica windows mounted in suitable mechanical assemblies are placed between resonator mirrors and laser cavity in such a way that the generated laser beam is out coupled through the resonator during the laser operation. The implemented decoupling assemblies isolate the caustic environment produced in low pressure laser cavity from that of resonator mirrors. Thus requirement of using isolation valves and cavity limbs between laser cavity and resonator as in conventional COIL source is eliminated. Such decoupling mechanism therefore effectively reduces the number of associated components as well as overall length of the laser source which in turn further reduces the overall weight of the laser making it suitable for use onto a mobile platform. Moreover the technique provides accrued benefits in terms of reduction in readiness time and checking of optical alignment of the laser source at will in practical operation scenarios.

Keywords: COIL; Laser cavity; Resonator; Decoupling; Isolation

1. INTRODUCTION

Chemical oxygen iodine laser (COIL)[1] is a high power chemical laser in which the required pumping energy for population inversion is released via a chemical reaction. This eliminates the need of electrical power supply for laser operation at remote locations. Among other chemical lasers, COIL has the advantages of power scalability, fairly short laser wavelength (1.315 µm) compatible with fiber[2] and also better laser material interaction. These attributes make COIL the choice for both military[3,4] as well as industrial applications[5]. The current literature[6-9] indicates that there are number of research activities related to advanced subsystems development and diagnostics for COIL in the US, Russia, Japan, Germany, Israel, Czech Republic, India, China, and South Korea.

COIL operates on the $I^*(^2P_{1/2}) - I(^2P_{3/2})$ transition of atomic iodine at a wavelength of 1.315 µm as

$$I^*\left(^2P_{1/2}\right) + h\nu \rightarrow I\left(^2P_{3/2}\right) + 2h\nu(1.315\mu m) \quad (1)$$

The atomic iodine (I^*) is populated by near resonant energy transfer from singlet oxygen molecules.

$$O_2(^1\Delta_g) + I(^2P_{3/2}) \Leftrightarrow I^*(^2P_{1/2}) + O_2(^3\Sigma_g) \quad (2)$$

Singlet oxygen is generated by the reaction between chlorine gas (Cl_2) and basic hydrogen peroxide (BHP) as given by the equation

$$Cl_2 + 2KOH + H_2O_2 \rightarrow 2KCl + 2H_2O + O_2\left(^1\Delta_g\right) \quad (3)$$

The interaction of singlet oxygen with atomic iodine at appropriate flow conditions results in the generation of laser gain medium inside the laser cavity from where the laser output power is extracted using optical resonator. In conventional COIL source, the laser effluents produced in the laser cavity during laser operation are kept separate from the laser mirrors using isolation valves and cavity limbs between laser cavity and resonator. These isolation valves are operated using actuators and associated circuitry. All these components increase the overall length and weight of the laser source. In addition, the increased length of resonator support structure corresponding to that of isolation valves, cavity limbs and rubber bellows also enhances the overall weight of the laser source. However military applications necessitate the deployment of mobile or transportable high power laser system of limited size and weight.

At Laser Science and Technology Centre (LASTEC), Delhi, the conventional COIL source has been technologically upgraded by implementation of decoupling interface between laser cavity and resonator which provides comparatively reduced-weight laser source suitable for mobile applications by reducing the number and length of components associated with the conventional COIL source. The reduced length of the laser cavity not only helps in reducing overall weight of the laser source but also makes resonator less sensitive to angular misalignment generated due to thermal gradient and gravitational displacement.

2. CONVENTIONAL COIL CAVITY CONFIGURATION

The conventional COIL source as shown schematically in Fig. 1 consists of various subsystems. BHP preparation tank is used to prepare BHP solution by mixing hydrogen peroxide and

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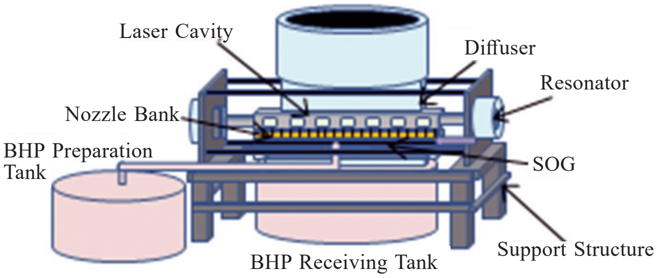

Figure 1. Schematic of COIL.

potassium hydroxide solutions in certain proportion. Singlet Oxygen Generator (SOG) where reaction between BHP and chlorine gas takes place is used to generate singlet oxygen molecules. BHP receiving tank collects back the BHP solution for further recirculation. Supersonic mixing nozzle bank is used for mixing the primary flow consisting of singlet oxygen molecules with nitrogen gas and secondary flow consisting of iodine molecules with nitrogen gas. The nozzle bank is followed by laser cavity wherein population inversion takes place and lasing phenomenon occurs. Optical resonator consisting of a set of mirrors is used for extraction of power from laser cavity. Diffuser is a low pressure system to exhaust the COIL effluents from sub atmospheric pressure to above atmospheric pressure.

The material used for laser cavity as shown in Fig. 2 is SS-316 due to its compatibility with chlorine. It has an active medium length of 350 mm with cavity cross-section of 60 mm x 60 mm. At one end, it is connected to the nozzle bank which ensures the entry of the laser gases into the laser cavity. At the other end, it is connected to the supersonic diffuser for exhaust of the effluent gases. An expansion of 4^0 is typically used to compensate the active medium boundary layer effect. The viewing window arrays with 7 view-ports on each side of the laser cavity are used to observe the chemical reaction occurring in the laser cavity. This helps in drawing the conclusion regarding the gain medium formation in the laser cavity.

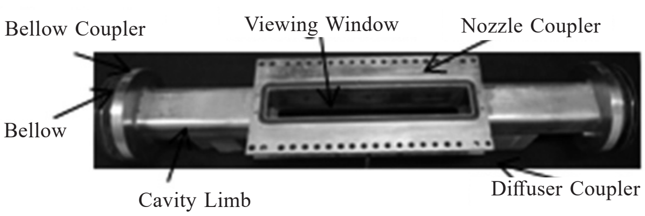

Figure 2. Laser cavity of COIL.

The laser cavity has cavity limb on both sides of it. The laser cavity through bellow coupler is connected with resonator flanges on the resonator assembly structure as shown in Fig. 3 using rubber bellows. These rubber bellows help in the alignment of the optic axis of resonator mirrors with the center of the laser gain medium and also keep the resonator insensitive to mechanical vibrations. The resonator support rods enhance the rigidity of the resonator flanges against vacuum created in the laser cavity. Resonator boxes are used to prevent the resonator optics from the sudden shock that occurs during evacuation of the laser cavity.

In high power COIL system, the laser cavity or gain region is typically separated from the resonator boxes using

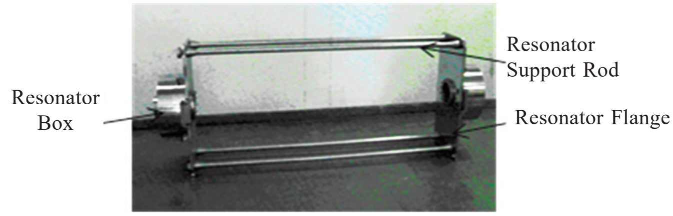

Figure 3. Resonator assembly structure of conventional COIL.

an isolation valve on each side of the cavity region. The two isolation valves and two cavity limbs along with rubber bellows increase the length of the COIL laser source. The conventional COIL source has typically 1000 mm separation between two resonator mirrors in comparison to 350 mm active medium length. It should also be noted that these systems are mounted onto support structure. The length of the support structure must be sum of the length of the laser cavity plus the lengths of the cavity limbs, the isolation valves and the bellow couplers. Such systems also include a vacuum pump and purge gases that are used to create the positive pressure in the resonator boxes so that the flow of the gases is out of the box and the gases do not flow back into the resonator boxes. It should be noted that back flow of the laser cavity exhaust may cause caustic damage to the precision optics inside the resonator boxes. It should also be noted that the optical isolation valves completely block the line of sight of the laser when not open. The closed valve prevents the monitoring of the optics within the boxes thereby limiting the ability to make adjustments to the optics for the alignment of the laser resonator. Each valve has an associated actuator system that also increases the mass of the laser source. Such laser source may be required to be mounted on transportable system. Reducing the overall size and mass of the laser source is appreciable to make it efficient for transportable system.

3. IMPLEMENTATION OF DECOUPLING INTERFACE

Figure 4 shows the schematic of the decoupling interface to be used to isolate the laser cavity from the resonator. In this technique, suitable mechanical assemblies of thickness 25mm made of aluminum as shown in Fig. 5 having heat and chemical resistant fused silica windows of 100 mm diameter and 10 mm thickness are placed on each end of the laser cavity to isolate the resonator mirrors in such a way that the generated laser beam is out coupled through the resonator during the laser operation.

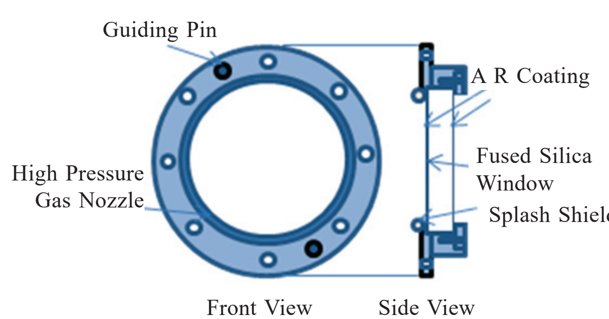

Figure 4. Schematic of decoupling interface.

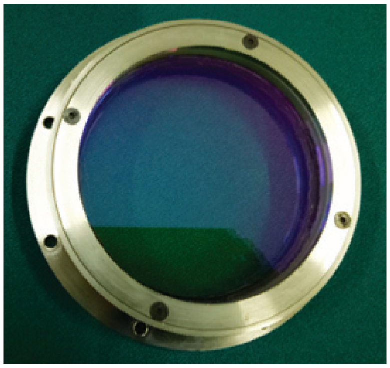

Figure 5. Developed decoupling interface hardware.

Fused silica windows have anti-reflective coating (R<0.5%) on both the surfaces at lasing wavelength of 1.315µm. The laser cavity is directly sealed against mechanical assemblies from both the ends. This allows resonator boxes to be non-pressurised which may further be removed. Mechanical assemblies include a high pressure gas source which may direct high pressure gas through the nozzles to wash the surfaces of optical windows to prevent the impingement of contaminants coming from laser cavity. Typically nitrogen gas at 2-3 bar pressure has been used in the laser experiments which does not react with the chemicals used in the COIL operation. In addition, a splash shield has also been disposed adjacent to fused silica window. The splash shield coupled to an actuator and a controller helps in preventing the caustic material within the cavity from contacting the optical windows during the period just prior to lasing.

The implemented decoupling assembly isolates resonator mirrors from the reactive laser gases produced in laser cavity. Thus requirement of using isolation valves and cavity limbs between laser cavity and resonator as in conventional COIL source is eliminated. The effective length of the laser cavity is therefore reduced from 1000mm to nearly 400mm, which also includes both decoupler interfaces. The resonator assembly structure remains of no use due to isolation between laser cavity and resonator. As a result of which total length of the support structure becomes shorter than the length of the structure earlier required. This effectively reduces the overall weight of the laser source. Therefore the present approach reduces 20 per cent to 30 per cent overall weight of the COIL source making it effective for mobile platform.

Since the decoupling interface isolates the low pressure laser cavity from the resonator mirrors, it greatly simplifies alignment of resonator optics. Once the resonator optics are aligned, the assembly is unaffected by the occurrence of shocks and vibrations occurred during COIL operation thereby eliminating the need for repeated alignment. Further, the alignment may be checked at will as there are no interfering isolation valves or shutter between the mirrors. The accrued benefit is also in terms of reduction in readiness time of the laser system in practical operation scenarios.

4. RESULTS AND DISCUSSION

At LASTEC, the conventional COIL source as described above has been technologically upgraded by implementing decoupling interface between laser cavity and resonator. The cavity limbs as well as the resonator assembly structure have been dispensed with and resonator mirrors are mounted separately. The laser cavity and resonator have been tested in conjunction with the rest of the subsystems of the COIL during the laser runs. The COIL source has been operated with the help of dedicated data acquisition and control system.

Laser test runs for typical COIL input parameters were carried out to make a comparative study and to prove the efficacy of decoupling interface. The liquid reagent (BHP) of a molar ratio (KOH : H_2O_2) of 6.5 : 7.0 was used at optimal temperature range of -20 °C to -18 °C to minimise generated water vapor at generator exit. Chlorine flow rate employed was nearly 450 mmol s^{-1} with a primary nitrogen dilution of N_2: Cl_2:: 2.5:1. The flow rates are precisely controlled using choked flow orifices. The generator efficiency is essentially a function of chlorine utilisation and singlet oxygen yield. The former is measured using in-house developed measurement setup based on absorption spectroscopy at 330 nm in which a portion of the singlet oxygen generator flow exit medium is passed through an optical cell of 25 cm length and 2.5 cm diameter. UV mercury lamp is used as a light source along with 330±5 nm interference filter. Collimated light is passed through the cell and detected using silicon photodiode (RS component stock no. 303-674). The molar flow rate of exit (residual) chlorine is estimated by calculating the partial pressure of chlorine (using Beer Lambert's law and perfect gas law) and substituting the expression for the partial pressure in Dalton's law. The detailed experimentations show a typical chlorine utilisation of greater than 90 per cent. Singlet oxygen yield is measured using optical emission spectroscopy based singlet oxygen diagnostic system. The details of the singlet oxygen measurement technique have been given by Mainuddin[10], *et al.* The emitted photons which are collected using a one-inch lens fixed in the diagnostic cell are focused on to a liquid nitrogen cooled germanium photodiode of 5 mm diameter (EG & G Judson, Model No. JD16-M204). An interference filter with 1270±5 nm wavelength is introduced between the lens and the photodiode. The estimated singlet oxygen yield at the exit of the generator inside the plenum is 60 per cent - 70 per cent. The observed flow rate of molecular iodine is nearly 10 mmol s^{-1}.

Figure 6 shows typically variation of pressures at various critical locations inside the gas dynamic tunnel of COIL laser source. The measured pressure at SOG, Plenum, Cavity and Pitot for both cases of conventional operation and operation with decoupling interface are shown. In both cases, Plenum ~ 20 torr, Cavity of 3- 4 torr and Pitot ~ 9 torr are found to be nearly identical, which clearly shows that the introduction of decoupling assembly does not in any way perturb the laser medium flow. There is marginal variation in SOG pressure from ~ 25 torr to ~ 20 torr owing to local effects of variation of condition of BHP injector plates and is apparently not due to introduction of decoupling interface. This is imperative for optimal functioning of the laser source. The small signal gain for the laser source is also measured using distributed feedback laser diode as a probe laser in conjunction with a germanium photo-detector. The observed small signal gain lies in the range of 0.0025 cm^{-1} - 0.003 cm^{-1} and remains unchanged for both cases.

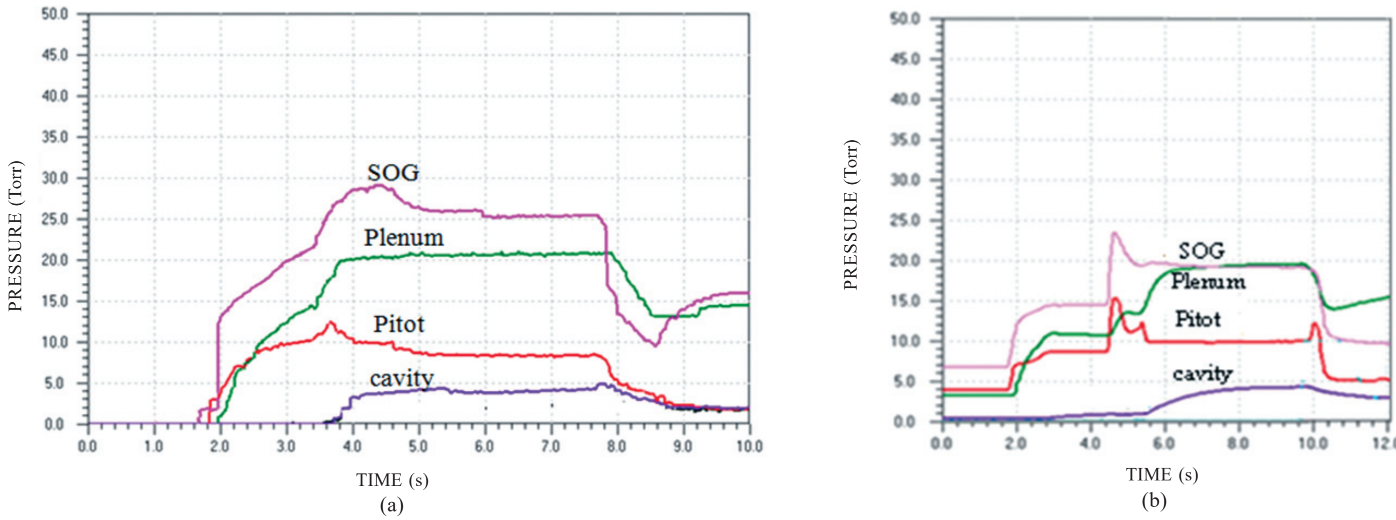

Figure 6. Temporal variation of pressures at different locations inside COIL: (a) Conventional and (b) With decoupling interface.

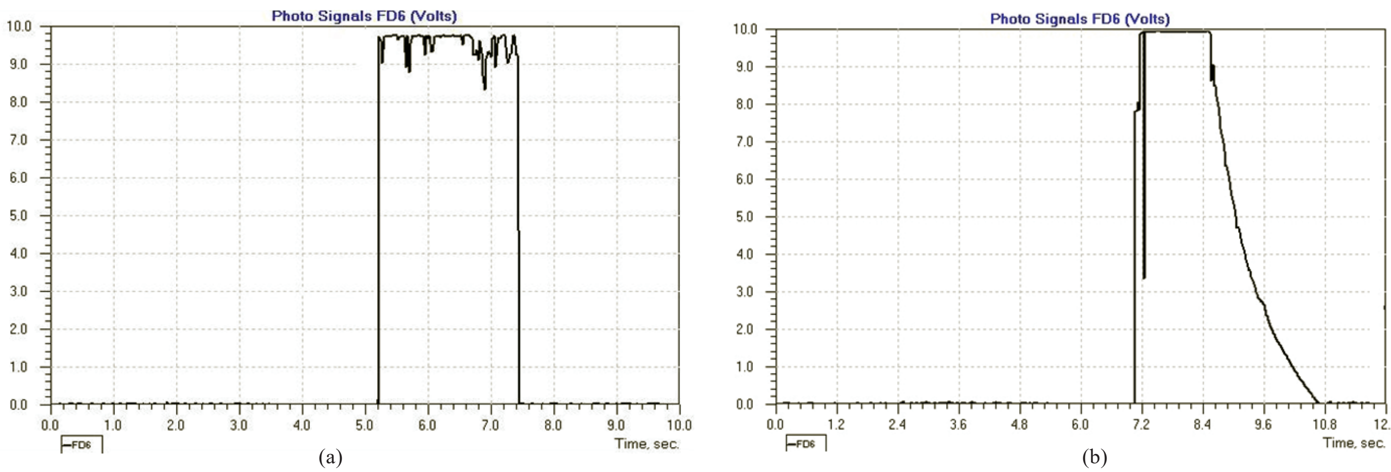

Figure 7. Temporal variation of laser power: (a) Conventional and (b) With decoupling interface.

The temporal variation of the laser power is measured using a germanium photo-detector by collecting the back scattered radiation from the rear mirror, refer Fig. 7, showing a pulse duration of ~ 2 s. A slight variation after 1.5 s showing signal trail off with decoupling interface is primarily due to the flutter of the guiding mechanism directing the back scatter into the detector.

The laser was operated repeatedly for its specified input parameters under both scenarios of conventional operation and with implementation of decoupling interface. The laser output power is measured using cone type laser calorimeter and has been shown in Fig. 8 for typical laser run case, which clearly indicates that the upgraded COIL source with decoupling interface provides nearly 10 kW stable laser output power which is identical to that obtained with conventional COIL source i.e. without decoupling interface.

In the present work, gain medium length as well as inter-mirror spacing of the COIL source has been kept same in both conventional and decoupling interface cases during experimentation. Therefore, longitudinal as well as transverse properties of the laser beam remain unaltered. Typical line width in case of multimode COIL systems with T~ 200 K and P~ 4 torr are reported to be 25 MHz[11]. The multi-mode laser

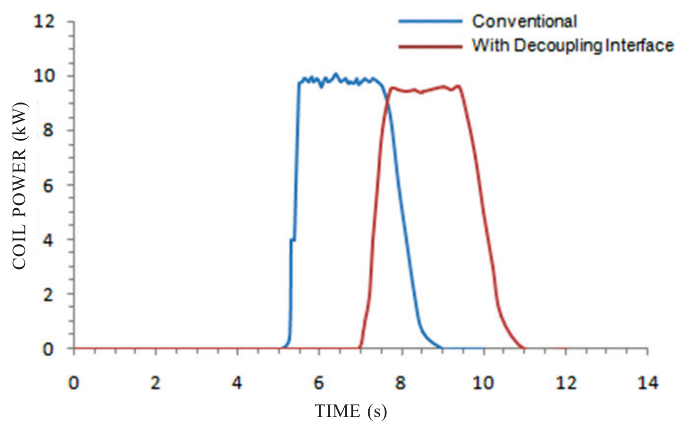

Figure 8. Temporal variation of laser power in both conventional and with decoupling interface.

output has been successfully achieved in both the cases in all the power runs. Exhaustive power runs for both operation cases have shown a typical maximum variation of 5 per cent. This is may possibly be due to insertion of two extra intra-cavity optical windows. Hence, it is inferred that the overall efficiency of the COIL source essentially remains unaffected by implementing the decoupling mechanism. Further, for large scale systems the benefits accruing from reduction in weight and volume of the laser cavity and resonator assembly far offset the marginal penalty on power output.

5. CONCLUSIONS

Practical operation scenarios require that overall footprint of the laser source as lucrative as COIL, which is capable of being scaled to large power levels in single aperture output, be reduced as far as possible. One of the contributing sub-system towards larger size and weight of COIL laser source is the resonator assembly. The present paper examines an alternative approach to implementation of resonator using a decoupling optical interface. This enables decoupling of the low pressure cavity flow field from the resonator optics and its effects thereof during system operation. The developed decoupling interface has been implemented in the COIL source and tested successfully showing a maximum typical variation of 5 per cent in power output as compared to conventional operation. Hence, it is inferred that overall performance of the COIL source essentially remains unaffected by implementing the decoupling mechanism. Further, for high power COIL systems the miniscule reduction in power, if any, is far compensated by largely diminished footprint of the laser source.

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CONTRIBUTORS

Mr A.K. Varshney received his MTech (Laser Technology) from Devi Ahilya University, Indore, in 1999. Currently, he is working as a Scientist at DRDO-Laser Science and Technology Centre, Delhi, India. His area of research includes : Integrated optics, microchip lasers and high power lasers specifically chemical oxygen iodine laser.

In the current study, he contributed towards the design, implementation and testing of the decoupling interface to isolate the resonator from the laser cavity of the chemical oxygen iodine laser.

Mr Rajeev Kr Dohare obtained his MTech (Electronics & Communication Engineering) from Amity University, Noida, in 2013. Presently, he is working as a Scientist in DRDO-Laser Science and Technology Centre, Delhi, India. His field of interest includes data acquisition and control/ electronics/ high power lasers.

In the current study, he has carried out data acquisition and control during operation and testing of the chemical oxygen iodine laser.

Dr Gaurav Singhal received BE (Mechanical Engineering) from JMI, New Delhi, in 1998 and PhD from IIT, Delhi, in 2008. Presently, he is working as a Scientist in DRDO-Laser Science and Technology Centre, Delhi. His research interests include : High power lasers, high speed unsteady flows, turbulent mixing, laser diagnostics, CFD techniques etc.

In the current study, he has contributed towards the design, implementation and testing of COIL source both with and without decoupling interface.

Dr Mainuddin received his ME from Delhi College of Engineering, Delhi, in 2003 and PhD in 2008 from JMI, New Delhi. He is presently working as a Professor in Department of Electronics & Communication Engineering, JMI, New Delhi. His research interests include : Optical diagnostics, high power lasers, data communication, optical communication and computer networks.

In the current study, he has been instrumental in design and realisation of data acquisition employed for the operation of COIL source with and without decoupling interface.