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# Technology Focus

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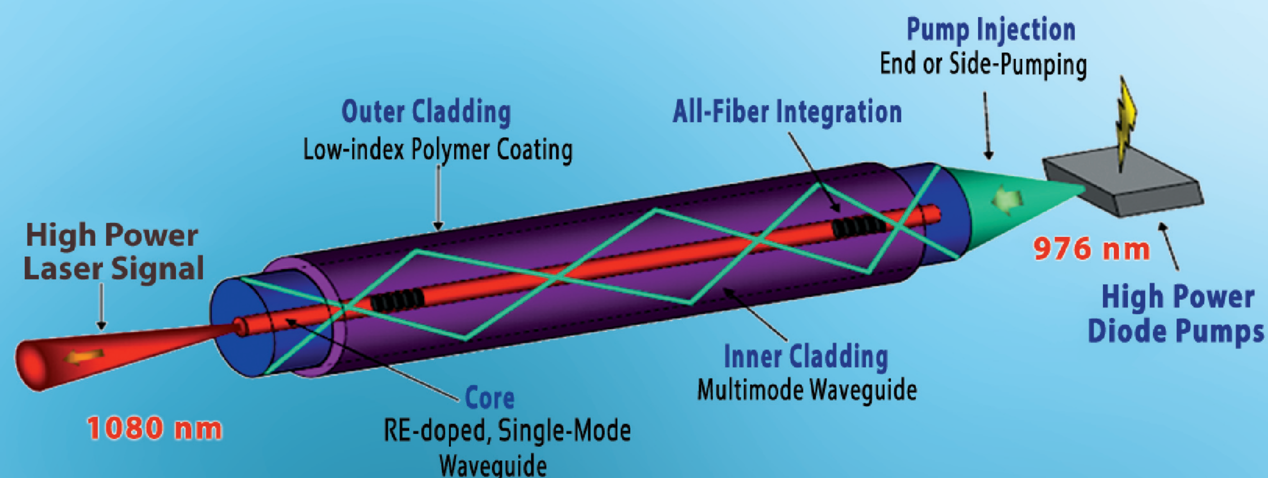
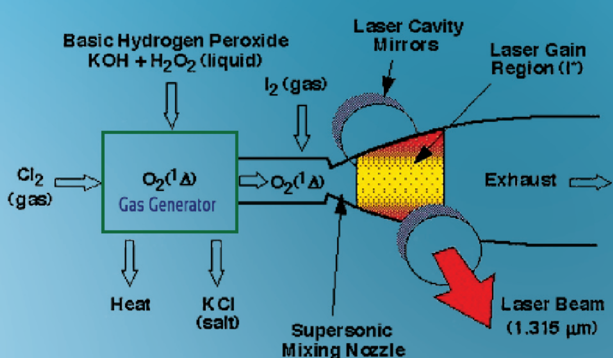
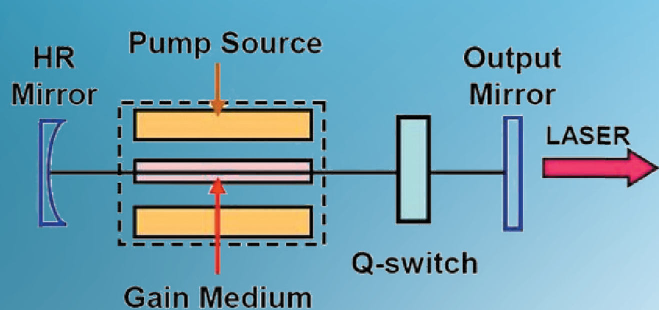
# LASER TECHNOLOGIES - I

## *Laser Sources*



# From the Desk of Guest Editor

Lasers have become an indispensable part of modern day battlefield. Depending on the wavelength and power; lasers have wide spectrum of military applications from dazzling human eye to shooting down a UAV, guiding munitions for precision strike, imaging enemy targets and detecting chemical, biological and explosive materials.

Laser Science and Technology Centre (LASTEC) is working for the development of laser source technologies for Directed Energy Weapon (DEW), dazzling and imaging applications. It is developing standalone sensor systems using different laser sources for applications like detection and location of optical targets and detection and identification of chemical, biological and explosive materials. Other laser systems developed by LASTEC include unexploded ordnance disposal system and different variants of dazzlers. LASTEC is also working in the area of electro-optic countermeasure systems and development of laser materials.

Over the years, LASTEC has acquired the expertise in designing, testing and evaluation of different types of laser sources and systems. Gas Dynamic Laser and Chemical Oxygen and Iodine Laser Sources of the order of tens to hundreds of kilowatts for DEW application have been successfully developed and demonstrated. Recently, single mode kW class Fiber Laser Source was realised in collaboration with foreign experts making India only the 6th (known) country to possess the requisite technological knowhow. Efforts are channelised in scaling the power levels of these laser sources.

Scientific principles and techniques like Raman scattering and its variants, laser photo acoustics, laser induced flouroscence, differential absorption, etc. have been aptly applied to develop a number of equipment for detection and identification of various chemical, biological and explosives warfare agents in field conditions. These equipment are at various stages of evaluation and have tremendous application in low intensity conflict operations.

A number of sub-system level technologies for building the most modern state-of-the-art laser systems for military applications have also been successfully developed. Expertise in associated technologies like beam pointing and tracking, embedded system design and thermal management has been achieved. FACET, a state-of-the-art facility for test and evaluation of laser systems has been established at Ramgarh, Chandigarh.

LASTEC is committed to provide world class laser sources and systems, using state-of-the-art technologies and complying to the world standards. The systems being developed are contemporary to those developed by the world leading military laser manufacturers and are appropriate to the Indian conditions.

The indigenous laser sources, equipment and associated technologies developed by LASTEC/ DRDO have been covered in two issues of *Technology Focus*. I hope this issue of *Technology Focus* will be useful in generating awareness about the tireless efforts of DRDO in developing cutting-edge defence technologies in the area of ***Laser Sources***.

**Hari Babu Srivastava**
Director
LASTEC, Delhi

# LASER SCIENCE & TECHNOLOGY CENTRE

Laser Science and Technology Centre (LASTEC), Delhi has its origin as Defence Science Laboratory (DSL) established as a nucleus laboratory of DRDO in 1950. In the beginning, DSL operated from National Physical Laboratory (NPL) building. Later in 1960, it was shifted to Metcalfe House. With passage of time, some of the specialising groups moved to different locations and came into being as full fledged laboratories/ centre/ establishments. In 1982, the DSL moved to its new technical building in Metcalfe House complex and was renamed as Defence Science Centre (DScC). In 1999, in view of the R&D thrust shifting to development of lasers, Opto-electronics and related technologies, the laboratory was rechristened as Laser Science and Technology Centre (LASTEC).

The DSL has seeded as many as 15 present DRDO labs, which includes Defence Research & Development Laboratory (DRDL), Solid State Physics Laboratory (SSPL), Institute of Nuclear Medicine & Allied Sciences (INMAS), Food Research Laboratory (FRL), Institute for Systems Studies & Analyses (ISSA), Defence Scientific Information & Documentation Centre (DESIDOC), Centre for Fire, Explosives & Environment Safety (CFEES), Scientific Analyses Group (SAG) and Institute of Technology Management (ITM). To start with, in 1950s, the research activities of the laboratory were mainly confined to operational research and ballistics. Electronics and communications, explosives, physiology, nuclear medicine research and food technology were added to its areas of research and study in 1960s. In 1970s, the laboratory consolidated its R&D activities towards more specific and application oriented areas, such as liquid fuel technology, spectroscopy, crystallography, and so on. The laboratory contributed significantly in missile programme in the areas of G-fuel and UDMH (for long and short range guided missiles), trajectory modeling and Joule-Thomson mini cooler and IR dome material, polyurethane for potting of electronic circuits, microphone grid (for locating gun position by sound ranging methods), air ventilated suits, etc. In 1982, DScC was given a new charter of duties with its major thrust on lasers. In 1986, the Centre was made responsible for the development of lasers for directed energy applications as one of its major missions. LASTEC has since established itself as a centre of excellence for the development of high power laser sources and related technologies, electro-optic countermeasure and battlefield opto-electronic equipment.

# HIGH POWER LASER SOURCES

High Power Laser Sources based Directed Energy Weapons (HPL-DEW) have emerged as one of the most revolutionary classes of weapons in the 21st century. Ground based deployment of laser based DEW for air defence against rockets and missiles has already been established. High power airborne laser has also been tested against ICBM up to a range of 150 km. Key technologies for space based lasers with very promising anti-missile and anti-satellite capabilities have also been proven.

Global influence of this new generation of high power laser sources based DEW can potentially re-write the ground rules for the future warfare doctrines and geo-political equilibrium in the 21st century.

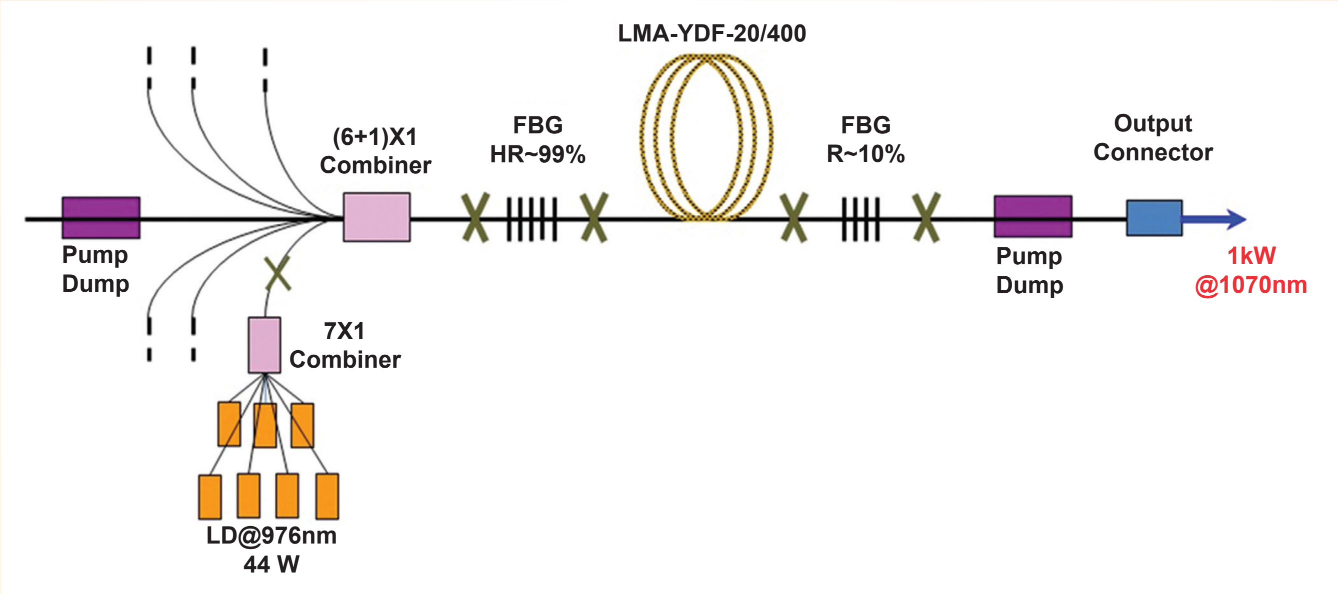
The technology has progressed significantly in the past decade and many nations are currently engaged in the rapid development of high power laser based DEW Systems. In India, DRDO is vigorously pursuing development work for both tactical and strategic DEW application. LASTEC has developed core technologies including Gas Dynamic Laser (GDL) and Chemical Oxygen Iodine Lasers (COIL) and demonstrated 100 kW (multi mode) GDL and 20 kW (single mode) COIL sources. In its sustained efforts towards development, work on high power fiber laser sources involving complex technologies has been initiated. LASTEC has developed 1 kW fiber laser through collaboration and development work of 5 kW and 9 kW fiber laser sources utilising complex beam combining technologies has also been initiated. Power output from these sources will be combined in space for tactical application. LASTEC has also initiated work on the development of pulsed fiber lasers for different defence applications.

LASTEC is investing heavily in many ongoing and futuristic laser source technologies. The ongoing program is a multi-pronged scheme for development of directed energy laser sources with concurrent technology upgradation efforts in specific technology areas to meet the future system requirements.

Under the ongoing program on high power laser sources, different technologies such as combustor, resonator, gas and chemical supply, exhaust control, singlet oxygen generator, thermal management, data acquisition and control system, fiber splicing, beam diagnostics, etc. have been developed and used for demonstration of high power laser sources.

## High Power Fiber Laser

Fiber lasers have become the disruptive technology in the field of lasers as they are adjudged superior to many of the established lasers for various applications. The recent advances in optical fibers and related technologies resulted in the development of High Power Fiber Lasers (HPFL) for industrial and defence applications. It has many proven advantages over other lasers. High efficiency, low thermal management constraints, small footprint, no requirement of logistic supply chain and above all good inherent beam quality make fiber lasers most suitable for platform integrated long-range DEW applications. Another major advantage of fiber lasers is that they are highly suitable for power scaling using different beam combining techniques. Development of very high average power fiber lasers (> 100 kW) is envisaged by many countries for building DEW systems for tactical military applications. As fiber laser beam is confined within the flexible fibers and requires no alignment or free space bulk optics such as lenses and mirrors, systems built using fiber lasers have significant advantage in harsh military environments. However, development of all-fiber single mode high power fiber lasers is very challenging and crucial for development of HPFL based DEW systems.




1 kW Fiber Laser Pumping Configuration

Fiber laser utilises very thin glass fibers doped with special materials to convert poor quality laser light generated by diode lasers to a high quality laser light beam. The fiber waveguide, which is composed of a glass core region doped with a rare earth material such as Ytterbium ($Yb^{3+}$) surrounded by a regular glass cladding region, confines the laser beam to the fiber core region where laser gain and amplification take place. Depending on the type of doping material used, the laser operating wavelength can range from 0.8 µm to 2.3 µm.

LASTEC has undertaken a TD project to develop HPFL technologies and necessary infrastructure to build 1 kW single mode fiber laser sources which can serve as basic building block for developing much higher power laser sources using different beam combining technologies. The most important element in the development of fiber lasers is rare earth doped double clad optical fiber which acts as gain medium. Newer gain media for the development of high power fiber lasers are being explored mainly in the form of large mode area photonic crystal fibers.

1 kW Single Mode Fiber Laser

In order to develop a robust fiber laser one needs to integrate/ fuse all the other elements of laser in to the gain medium by means of fusion splicing. All fiber spliced 1 kW fiber laser is developed based on a single end pumping configuration using a Large Mode Area (LMA) $Yb^{3+}$ doped fiber (LMA-YDF-20/400) with core diameter of 20 µm and inner cladding diameter of 400 µm. Fiber length has been optimised for the required gain and output power. Fiber laser cavity is formed by two Fiber Bragg Gratings (FBGs) one at pumping end with high reflectivity of ~99 per cent (signal wavelength) and the other at output coupler side with reflectivity of about ~10 per cent (signal wavelength).

A large number of high power pumping laser diodes emitting at a wavelength having high absorption efficiency for fibres, are combined by pump/ signal combiners. To protect the diodes from unwanted back reflections. A pump dump is used after the output coupler FBG. Output of the pump dump is spliced into a high power delivery fiber connector assembly terminated by a cooled fiber end-cap/ collimator.

LASTEC with the help of a collaborator has developed one unit of 1 kW single mode fiber laser with output beam quality parameter $M^2$ value of 1.12.

One more unit of 1 kW fiber laser is currently under development. Though there are several critical technologies involved, fusion splicing of all fiber components with lowest light loss is critical to make a monolithic robust structure which is alignment free and compatible for field deployment.

LASTEC also envisages to develop different types of beam combining technologies to develop much higher power fiber lasers with beam quality parameter $M^2$ close to unity for the use of long-range laser propagation and DEW applications.

## Pulsed Fiber Laser

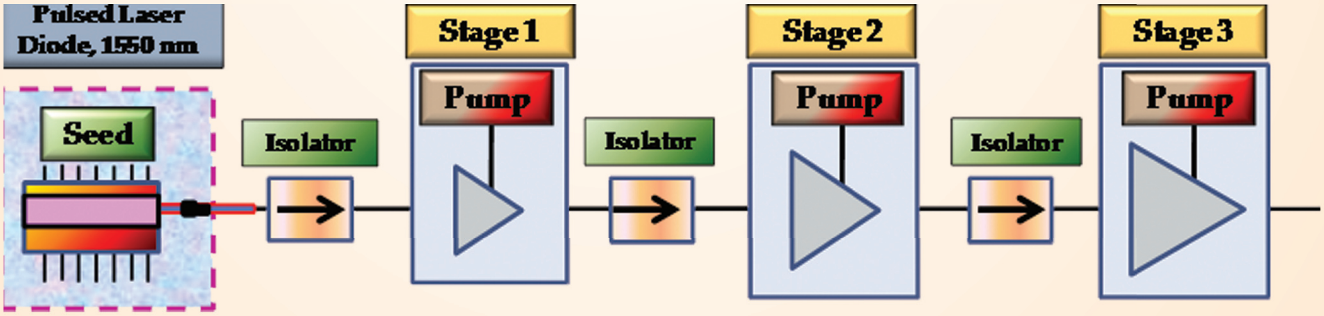
Pulsed Fiber Lasers (PFLs) are rapidly replacing the conventional Q-switched bulk solid state lasers for generating nano second pulses at multi-kHz repetition rates. Such lasers are required for various long range applications like remote sensing, imaging, LIDAR, etc. Advantages offered by fiber based solutions include simpler thermal management, higher efficiency, flexible pulse format and waveguide defined beam quality independent of power level. Fully integrated structure in fiber laser provides compact, robust, alignment free laser that is compatible with highly efficient fiber pigtailed high power pump diodes and various fiber integrated devices such as FBG, fiber couplers, etc.

LASTEC has recently initiated work on this very challenging domain of developing different pulsed fiber laser sources involving Ytterbium and Erbium doped fibers to generate 1.0 μm and 1.5 μm wavelengths respectively at high repetition rates. These sources are required for long range applications like target illumination, dazzling, etc.

A fiber laser is pumped by high power multi mode single emitter diode bars, typically through a cladding surrounding a single mode core. This single mode core is typically 5 to 12 μm in diameter. The double clad fiber consists of an inner single mode core doped with the appropriate rare earth ions such as Ytterbium, Erbium, Neodymium and Thulium. The cladding is made of undoped glass that has a lower index of refraction. The pump light is injected into the cladding and propagated along the structure, passing through the active core and producing a population inversion. The emission wavelength is a function of choices in the doped fiber and by type of reflector, e.g. Bragg Grating. Traditionally, intense nanosecond laser pulses are generated with Q-switching techniques. However, a low power pulsed seed source, e.g. a gain switched laser diode may be employed whose output may be amplified to substantial energies with a fiber amplifier chain. With this approach one can easily change the pulse repetition rate and output pulse energy without changing the pulse duration, or can change the pulse duration and shape without affecting other pulse parameters. In a Q-switched laser, such flexible parameter control is not possible; e.g., lower pulse energy usually implies longer pulses.

### Critical Areas

To get high beam quality, single mode waveguide structures are required. A small core clad numerical aperture is used to maintain the single mode transmission but it also leads to intense power density in a small core area, which brings strong nonlinear effects such as Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS) and Amplified Spontaneous Emission (ASE), which can limit the maximum output power of fiber lasers. The use of large core or Large Mode Area (LMA) fibers helps in reducing optical intensity and prevent these parasitic effects. Recently peak powers ~1 MW have been reported in combination with multi-watt average powers. The LMA in conventional fibers,




Fiber Amplifier Chain

however, leads to multimode propagation leading to degradation of beam quality. Therefore novel fibers called Photonic Crystal Fibers (PCF) have been the subject of intense research in recent years.

Development of pulsed fiber laser sources would require several critical components with high damage thresholds to sustain high peak power densities. These components include LMA doped delivery fibers, high power pump laser diodes, isolators, pump combiners, couplers, filters, etc.

Significant advances in high power diode pump lasers, refinement of power scaling and energy storage techniques, fiber component fabrication such as FBG are opening up the way for the development of active fiber systems that can deliver tens of watts of single transverse and longitudinal-mode output power, millijoule pulse energies, and ultrashort pulses with peak powers in the 10-100 MW region.

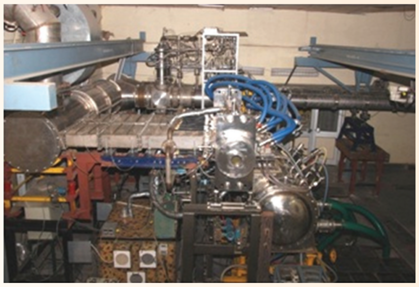
Furthermore, advances in nonlinear optical materials are permitting these high-power fiber laser outputs to be efficiently converted to the visible and near infrared (IR) spectral regions. This would require Polarisation Maintaning (PM) components.

For the industrial, scientific medical and defence applications fiber lasers offer wide wavelength range. Availability of narrow linewidths, polarised or unpolarised emissions, short pulse durations, single mode operation, insensitivity to environmental conditions and compact size are some of the advantages only fiber lasers can accomplish.

## Chemical Oxygen Iodine Laser (COIL)

Chemical Oxygen Iodine Laser (COIL) systems are amongst the most important candidates in the class of High Energy Laser (HEL) systems for strategic applications. COIL systems provide several unique advantages such as good atmospheric transmission characteristics and short wavelength (1.315 mm) which facilitates reasonable spot size at long ranges with manageable optics. COIL is a low pressure system (cavity pressure ~ 3-5 torr) and offers extremely good beam quality, exhibits potential for greatly reduced production costs due to the use of plastic parts throughout the device. COIL is capable of being scaled up to MW class power levels in a single aperture output and has been tested against cruise missiles.

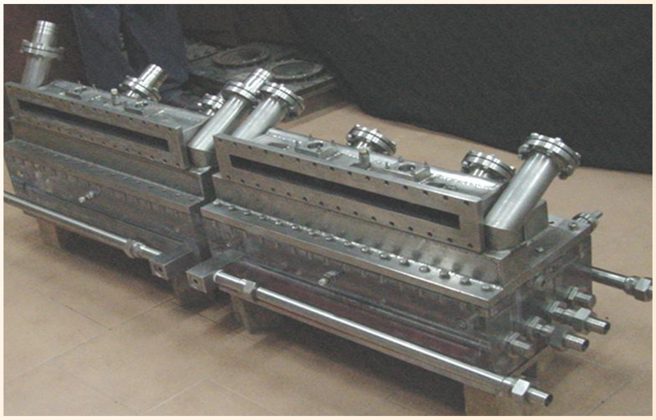
(a)



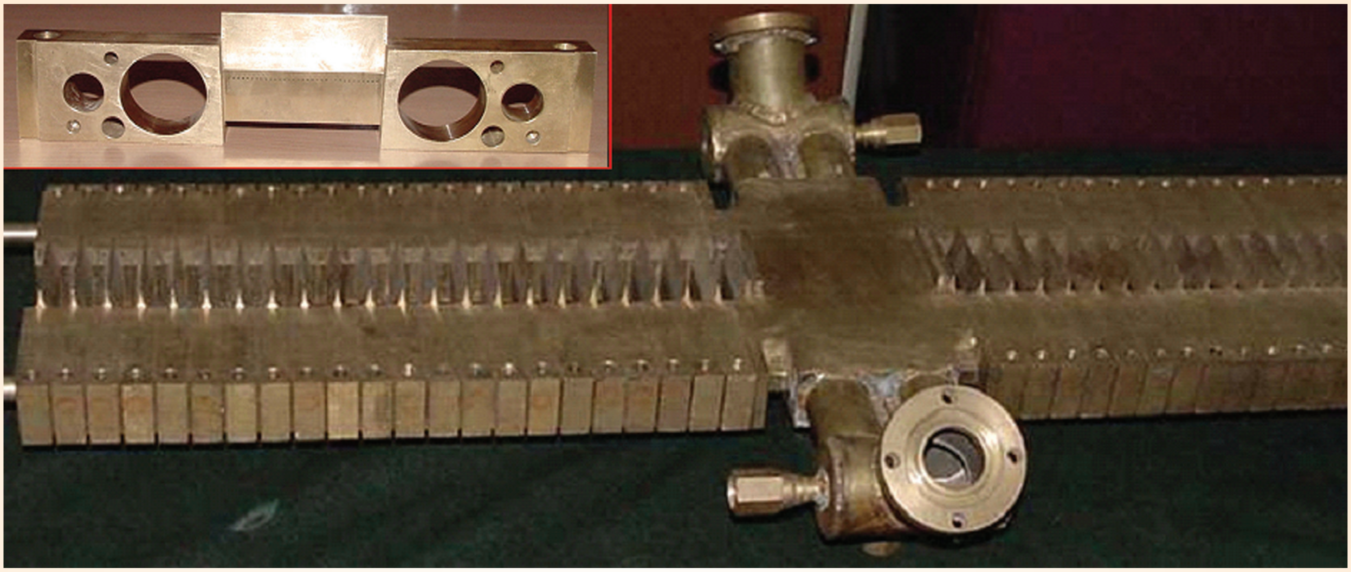
(b)

High Power COIL Sources
(a) 10 kW (b) 20 kW Direct Exhaust COIL

COIL requires singlet oxygen for lasing. Singlet oxygen is generated by reaction of basic hydrogen peroxide liquid and chlorine gas. Singlet oxygen is diluted with the carrier nitrogen buffer at low pressure (few tens of torr). This mixture of nitrogen and singlet oxygen is then mixed with iodine vapour (iodine being the lasing species). The mixture is then passed through the throat of supersonic nozzle and expanded into the laser cavity to achieve lasing action.



Jet Based Singlet Oxygen Generator for 20 kW COIL



Supersonic Nozzle System for 20 kW COIL

The laser effluents are thereafter exhausted to an evacuation system (vacuum dumps, pumps, or both) or a pressure recovery system (ejector, cryosorption, cryo-condensation)

LASTEC successfully developed and demonstrated its first small scale COIL system delivering 350 W power output in 2001.

With a view to address the technological gap, a ground based 10 kW COIL was developed through collaborative efforts and was successfully demonstrated in 2002 through vacuum dumps. Technological gains from the earlier realised COIL systems led to successful development and demonstration of ground based direct exhaust 20 kW COIL system.

Development of a COIL system is highly multidisciplinary in nature involving technological challenges. The subsystems which involve most critical technological challenges are: singlet oxygen generator, supersonic nozzle system, exhaust control system and optical resonator.

LASTEC has worked extensively on jet based singlet oxygen generators which were utilised in all the three COIL systems developed indigenously.

LASTEC has also worked on various versions of supersonic nozzles, viz., slit nozzle, subsonic iodine injection grid nozzle, advanced nozzle and winglet nozzle. Optical resonators with single and multiple pass geometries have also been developed and used in demonstration of high power COIL systems.

Present thrust is to address the challenges in the development of some of the most critical technologies and the new concepts which form possible solutions for compact futuristic high power COIL systems. The foremost being the development of high pressure singlet oxygen generator with operating pressure in the range of 80-100 torr with high throughput operation.

The other crucial technological area of research is high efficiency transonic supersonic nozzle system capable of providing higher small signal gain.

LASTEC is extensively working on these critical technological areas for planned development of 30-100 kW vehicle mountable sealed exhaust COIL systems with $M^2 < 2$ to achieve strategic application goals.

## Gas Dynamic High Power Laser based Directed Energy System

LASTEC's ADITYA project was an experimental test bed to seed the critical DEW technologies. The Gas Dynamic High Power laser based Directed Energy System can be broadly divided into two major subsystems: Laser Power Source and Beam Delivery System. Laser power of the order of 100 kW is required to cause the stipulated damages at 0.8 km and 2.5 km distance using a 0.7 m aperture telescope. The beam delivery system has to simultaneously perform several roles. It acquires and tracks the distant static and moving target in real time and points and focuses the laser beam on the target. The adaptive optical system has to compensate for the jitter and wave front distortion of the laser beam from the source. The technology related to laser source, beam delivery and issues related to system integration on mobile platforms have been addressed during the execution of the project. It would be a useful input to future laser weapon programmes of DRDO.

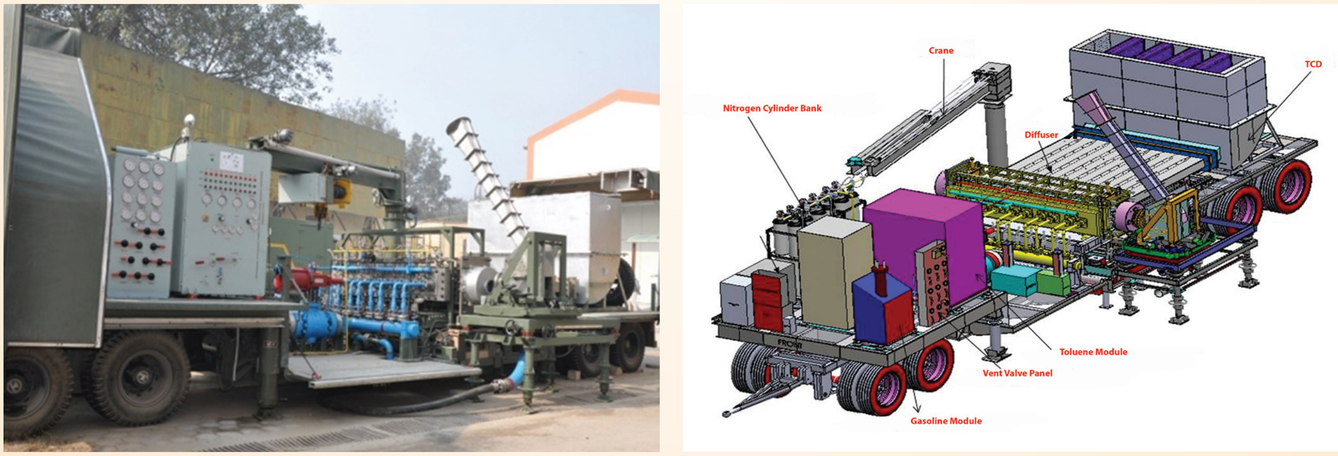
## Laser Power Source of 100 kW

The laser source consists of system integrated on different transportable platform, viz., Laser Generation System Vehicle (LGV) and Air Supply System Vehicle (ASV). The system has been realised, integrated, and tested. Laser power of the order of 100 kW has been achieved. Damage potential of the laser has been tested up to 800 m distance.

**Laser Generation Vehicle (LGV)** has been developed to generate a high energy beam. The input energy is pumped into the system through combustion of large amount of air and toluene. The system mainly consists of laser tunnel, toluene storage, gasoline storage and pressurisation and feed system, parts of combustion, ignition, aerodynamic window, cavity bleed, fuel purging, pneumatic air supply lines, control panel, etc. The laser tunnel consists of a combustor, a nozzle bank with cavity, resonator, diffuser and TCD. These systems are mounted on a low bedded transportable trailer having suitable canopy. The LGV is dependent on ASV for oxidiser air supply and command control vehicle for operation commands for generation of high energy beam. The associated technologies developed are:

### Toluene - Air Combustor System for Generation of Lasing Gas Mixture @ 40 kg/s

- To withstand the high temperature (tens of hundreds) and high pressure (many tens of bar) condition for the repetitive firings
- Soot free combustion & generation of $CO_2$, $N_2$, $H_2O$ and $O_2$ in required proportion
- Reliable ignition system through pilot flame igniters to avoid any ignition delay




Laser Generation Vehicle (ADITYA)

- Four level of safety interlock for controlled combustion

### Supersonic Multi Bank Contoured Nozzle

The technical challenge lies in maintaining a small uniform throat gap with a tolerance of few μm in all the nozzle blades arranged as an array. The blades can be dismantled for replacement. The blades, aerodynamically contoured, were fabricated with the help of wire cutting machining. The blades have been fabricated with inconel material.

### Resonator Cavity along with Mirror Protection System

A mirror protection system consisting of pneumatic shutters and cavity bleed was incorporated in the laser cavity to safeguard the optical mirror. The shutter protect the mirror from soot and shock which comes off with the initial flow. The cavity bleed takes care of the mirror during firing.

### Direct Discharge Supersonic Diffuser

An efficient atmospheric discharge is very important for the transportability of the system. It recovers pressure from very low values to atmosphere pressure for atmospheric discharge. The art of diffuser design has been understood through theory and experimentation.

### Vortex Aerodynamic Window

Aerodynamic window permits the extraction of laser beam from the cavity of a high power laser through a non-absorbing gas curtain that supports a pressure difference between the cavity and ambient atmosphere. A vortex type aerodynamic window was developed and used with unstable resonator.

### Vibration Isolated Resonator

A vibration isolated structure is mounted in such a way as to prevent transmission of tunnel and platform vibrations to the resonator. This helps in providing the desired beam stability.

### Data Acquisition & Control System

Distributed type of data acquisition and control system was developed. Command control vehicle controls the laser firing operation through firing and safety cyclograms. Different type of temperature and pressure sensors and control valves mounted on ASV, LSV and Beam Delivery Vehicle are monitored and controlled through command control vehicle.

### Air Supply System Vehicle

Air storage and supply system delivers the compressed air at different pressures and different flow rates to various systems. It consists of high

Air Supply Vehicle (ADITYA)

pressure air generation, storage and supply system. In this system large quantity of air is stored which is required at the time of laser test firings. Air is required in many sub-systems like main air to combustor, air to igniters, air to aero-dynamic window, air for pneumo-pusher, cavity bleed, air for mirror protection and aerodynamic window shutters, air for Remotely Operated Valves (ROV), air for purging of main fuel and igniter fuel lines, intermediate cooling, etc. This vehicle is capable of supplying up to 50 kg/s mass flow rate of regulated air for combustion, aero window and other miscellaneous purposes.

## Command Control System

The command control vehicle is an ISO type air conditioned EMI protected shelter to control the operation of laser source and beam delivery on the target from a safe distance. This is achieved through two control consoles for the GDL source and beam director mounted into the command control vehicle. The GDL control console is capable of laser testing the operation of various valves and conducting laser firing. It is very critical to acquire data from the field sensors on LGV, ASV, BDV, and controlling all the subsystems for remote firing control. The safety interlocks have been implemented based on pressure in igniter and combustor for avoiding any pulse which can damage the system. The beam director console is capable of independently acquiring the information of the target and the delivery of laser beam on to it.

## Power Supply System Vehicle

The power supply system is mounted on a DG set vehicle. It houses three DG sets. Two numbers of


Command Control Vehicle (ADITYA)

Power Supply System Vehicle (ADITYA)

higher power DG sets are used to run the compressor placed on air storage and supply trailer. The third lower capacity DG set caters to the charging needs of various UPSs placed in other trailers/ vehicles and other electrical requirements of the DEW system.

## Beam Delivery System

The beam from laser source is coupled to the beam delivery system. The focusing telescope is mounted on a gimbal which should be agile enough to keep the beam focused on the same spot. The gimbal has to work in closed loop with video tracking system.

The main objective of the Beam Directing System (BDS) of Project ADITYA is the auto focusing of the high power laser beam onto a distant moving target in the required operating range. The BDS consists of mainly two assemblies, one is beam transport system and other is stabilised gimbal platform assembly. The stabilised gimbal platform along with beam directing

Beam Delivery System (ADITYA)

electronic system is responsible for controlling the overall functionality of the system.

- The beam directing telescope is one of the most critical subsystems of the laser beam director which is responsible for coupling the laser power from the source to the target and for precise pointing/ focusing of laser beam to achieve the required power density on to the area of interest on the moving target at the operating range and for the entire duration of the laser radiation.
- Target acquisition and video tracking is used to detect, identify and track the moving airborne targets, so that high power laser beam can be fired on the vulnerable spot of the target. Once the target is acquired, detected and identified, the lock on and tracking gets initiated. As the target comes closer to the beam director, then area of interest, i.e. vulnerable spot on the target is locked and tracked.

Dual Axis Stabilised Gimbal Assembly Integrated on BDV (ADITYA)

### Test and Trials of the System

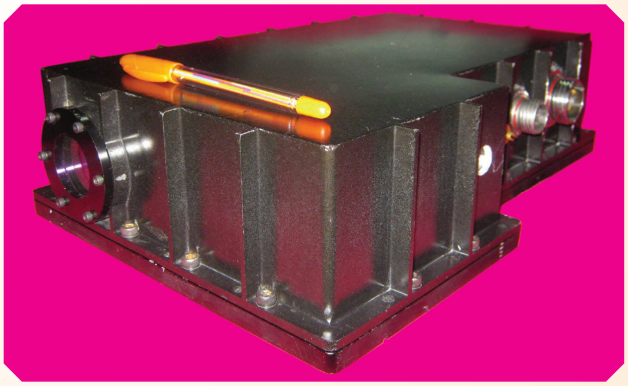
The beam was focused on the far field targets with the help of Basic Beam Director (BBD) and gimbaled telescope mounted on the Beam Delivery System Vehicle (BDV). Damage potential on various types of targets (stacks of mild steel plates, perspex, GFRP, optical glass, etc.) has been established.

## Solid State Lasers

At LASTEC, different types of solid state laser sources have been designed and developed in the past few years.

### Eye Safe Lasers

Lasers operating around 1.5 µm have the highest permissible ocular exposures accepted by the ANSI 2.136.1-1993 standard (1 J/cm$^2$ for single pulses). This wavelength is not only eye safe but falls in the window of atmospheric transparency and is absorbed by OH-groups and many organic substances. Also, there exist fast response and high sensitivity photo-detectors for this particular wavelength. These factors make it a highly promising candidate for applications in range finding, pollution monitoring, medicine, communication and spectroscopic research. At LASTEC, different techniques of eye safe wavelength generation have been established including direct generation through Er: Glass, optical parametric and Raman conversion techniques.



Eye Safe Laser Source for LACSMI

### Eye Safe Laser for Laser Cross-section Measurement Applications

An intracavity OPO converted, diode pumped and solid state electro-optically Q-switched Nd: YAG laser, capable of generating 8-10 mJ, ~ 5 ns at eye safe wavelength of 1570 nm with variable divergence has been designed and developed. Thermo Electric Coolers (TECs) have been employed to maintain the optimum temperature of laser diode arrays and the combined heat load from the pump chamber and TEC is distributed over the system base plate with embedded heat pipes. Such cooling mechanism has eliminated the requirement of fins and fans in the laser system. Laser has the capability of programmable duty cycle and pulse repetition rates.

## High Energy High Repetition Rate Eye Safe Lasers

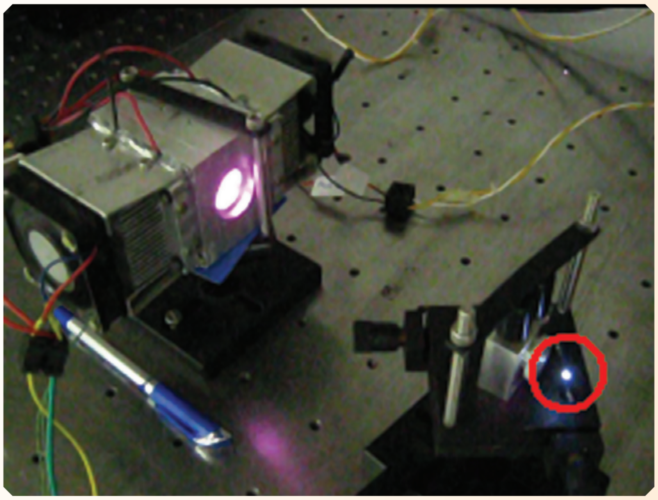
Two experimental prototypes of high energy eye safe lasers have been jointly developed with BI Stepanov Institute of Physics, Minsk, Belarus. One laser is based on Er:Glass laser which directly generates the eye safe wavelength 1540 nm with ~ 25 mJ energy at 20 Hz. Other laser is based on OPO shifted Nd:YAG laser and generates 50 mJ @ 20 Hz at 1570 nm.

Er: Glass Laser

OPO Shifted Nd:YAG laser

## Miniature Diode Pumped Solid State Lasers

Miniature diode pumped solid state lasers offer high power density (output power to volume ratio) and thus are desirable for most applications requiring small laser footprint. These applications include military, homeland security, instrumentation, materials processing, space and remote sensing. In addition, with proliferation of battery powered applications including laser flashlights, dazzlers, and other electro-optic modules that utilise modern high density lithium battery technology, require miniature laser sources with minimum volume and power consumption. Efficient mini lasers also minimise the volume and weight of the control unit used to provide electrical power and cooling functions to the laser head.



Miniature Diode Pumped Solid State Laser

## High Peak Power Monolithic Miniature Diode Pumped Nd: YAG Laser

A monolithic, diode, side-pumped and passively Q-switched $Nd^{3+}$ : YAG / $Cr^{4+}$ : YAG composite laser generating ~ 3 MW peak power pulses at 20 Hz with 15 mJ energy in 5 ns duration has been designed and developed. The compact and robust laser is suitable for variety of applications including range finding, designation and Laser Induced Breakdown Spectroscopy (LIBS). Air breakdown has been demonstrated by focussing the laser output.

## Liquid Lasers

The prime concern for any high power laser system is the ease of generation of laser medium and its pumping accompanied with efficient thermal management ensuring a compact laser system with high efficiency and near diffraction limited beam quality. This is best achieved by means of utilising a flowing lasing medium.

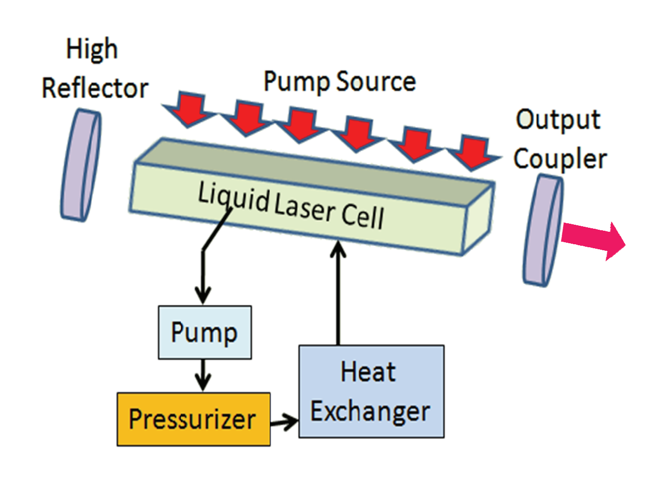
An approach in this direction is the use of liquid lasers. These basically employ aprotic lasing fluid impregnated with rare earth metals such as $Nd^{3+}$and $Yb^{3+}$ filling the optical cavity for lasing action. The thermal issues are overcome by circulating the liquid laser media using a pump and heat exchanger assembly allowing the replenishment for desired beam quality.

This is a new and upcoming technology having potential of generating hundreds of kilowatt in most compact form factor. LASTEC has also initiated work on this type of laser source.

Neodymium based liquid laser would essentially consist of Neodymium (III) Phosphorous Dichloridate retained in solution with Phosphorous Oxy-Chloride ($POCl_3$) by addition of a Lewis acid such as Zirconium Chloride ($ZrCl_4$). Lewis acid is desirably included in the solution to increase solubility of neodymium (III) phosphorous formed, optimise the intensity of fluorescence of the liquid solution and its operative efficiency.

Also, Neodymium Trifluoraceate which is dissolved in $POCl_3$ for generating Neodymium (III) Phosphorous Dichloridate is required to be synthesised by mixing Neodymium Oxide ($Nd_2O_3$) and Trifluoroacetatic Acid ($CF_3COOH$) followed by evaporation of excess water.

The liquid laser solution of $POCl_3$:$Nd^{3+}$:$ZrCl_4$ is highly stable over relatively long periods of time and does not degrade under flash excitation. It forms the basic part of the laser cavity.



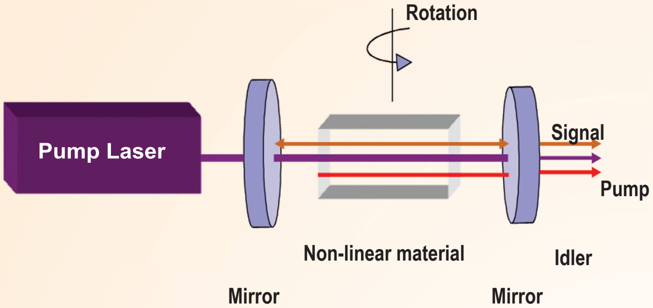

Schematic of Liquid Laser

Liquid laser system consists of a lasing chamber through which the lasing medium is circulated in a closed loop. A diode array used to excite the liquid lasing medium is located within the lasing chamber. A pump and a pressuriser along with a heat exchanger (shell in tube/ plate type), circulate the lasing fluid in a closed loop. The lasing chamber is then enclosed by the optical resonator at the two ends defining excitation volume for laser power extraction.

LASTEC also plans to develop rare earth metal doped liquid laser as it is a potential high power laser source with single aperture output. The technological areas of research pertaining to this laser include the kind of usable aprotic solvent, rare earth metals impregnable into the solvent and synthesis of liquid laser solution.

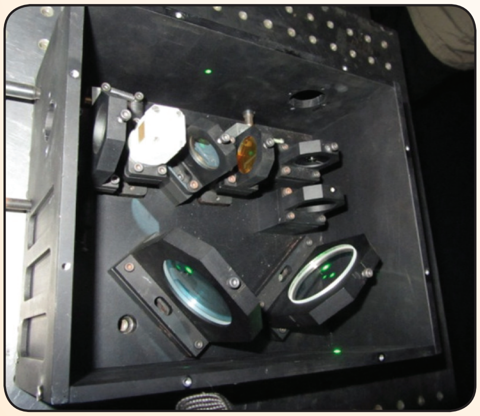
## OPO Based Tunable Laser Source

Most lasers are single wavelength devices, or have only a restricted range of multiple wavelengths due to the inherent physical properties of the gain media used. The most widely used wavelength-tunable coherent radiation sources are dye lasers and Quantum Cascade Laser (QCL). Each dye has a rather limited tuning range of about 5 to 20 nm in the visible part of the spectrum and tunablity of QCL is also limited to about 200 nm. However, lasers based on optical parametric wavelength conversion are more efficient and widely tunable than dye lasers.

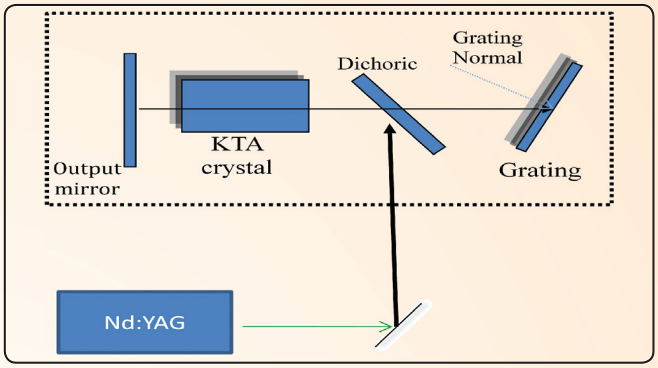



Schematic of an OPO

Optical Parametric Oscillator (OPO) is basically a non-linear optical device which provides tunable radiation from fixed laser source through parametric generation. In simple form it consist of a pump laser and a nonlinear crystal in a cavity. Laser based on optical parametric processes provide wide and continuous wavelength coverage of more than 1000 nm, easy and rapid wavelength tunability, high energy output and has the inherent advantage of being all solid state. In the recent past, LASTEC has worked on various OPO systems. KTA crystals have very high non-linear coefficient and damage threshold making it possible to achieve the OPO oscillation at relatively low threshold value. Cavity is made of plane mirrors of appropriate length, with direct/ side entry of pump beam through the cavity mirror.

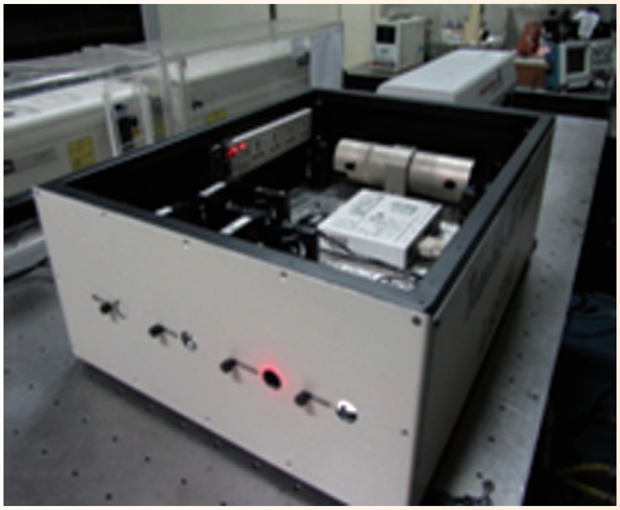


Side Pumping OPO Unit




Schematic of Narrow Linewidth OPO

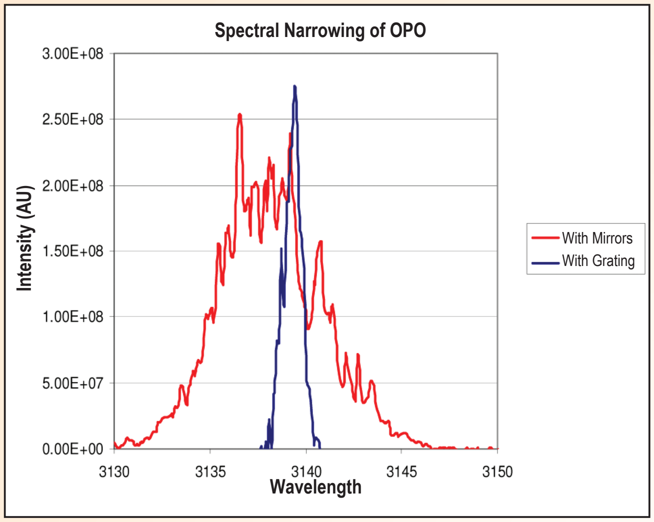
The module can be conveniently placed in front of pump laser to get the OPO action.



Solid State Tunable Infrared Source

Output from an OPO is broader in linewidth. To have a narrow linewidth, cavity is modified to a mirror grating cavity by introducing a wavelength selective element in the cavity. A system consisting of mirror grating cavity in littrow configuration using high precision motorised rotation stage has been developed.

LASTEC has designed and developed a solid state tunable infrared source emitting in the wavelength band 2- 4 μm and 8-15 μm. ***A patent "Incoherent Infrared Source Tunable from 2-18 μm" for the design has also been filed.***




**Linewidth Narrowing of OPO Output**

## Adaptive Optical System for High Power Lasers

Adaptive optics is an integral part of the DEW system. In order to achieve maximum lethality, a steady and nearly diffraction limited focused spot of a high power laser should fall at a desired location in the target plane. However, achievement of such a spot is exceedingly difficult because of the aberrations, inherent in the source or those induced by atmospheric turbulence. Aberrations in the source are due to in-homogenous lasing medium, distortions of optical components due to thermal loading and platform instabilities. Atmospheric turbulence is the main cause of distortions in the laser beams which are propagated over long path in the open atmosphere. Atmospheric turbulence, which is a highly complex, unpredictable and dynamic phenomenon, affects the laser beam in many ways that include beam wander, beam spread and scintillations. All these effects taken together drastically reduce the on–axis intensity of the beam on the target and results in the formation of a spot which is many times larger than the one predicted by diffraction theory.

An Adaptive Optical System (AOS) corrects laser beam aberrations in real time, thereby achieving maximum power density on the target. An AOS essentially consists of a wave front sensor, a wavefront corrector and an analog or digital control processor, as well as optical and electronic support hardware. The wavefront sensor detects the wavefront aberrations, the control processor quantifies wavefront errors and generate command signals to modify the surface profile of a wavefront corrector to compensate for the wavefront errors. Shack Hartmann wavefront sensor is one of the most commonly used system for measurement of wavefront errors. It divides the entire wavefront into large number of zones using a two dimensional array of micro-lenses and measures localised tilt errors in the wavefront using a Charge Coupled Device (CCD) or Complementary Metal Oxide Semiconductor (CMOS) camera. The localised tilt errors are then corrected using a deformable mirror (wavefront corrector). Stacked Actuator Deformable Mirror (SADM) and Bimorph Deformable Mirror (BDM) are other wavefront correctors most commonly used for DEW applications.

A BDM employs two piezo discs, with opposite polarisations, glued together. Any voltage applied across the two ends of the piezo actuator so formed produces expansion in one plate and contraction in the other. This results in bending of the piezo discs like a bimetallic strip producing similar deformation in the reflecting mirror bonded firmly to these piezo discs. Separate addressing electrodes on the free surface of piezo discs result in localised deformation of the mirror.

Besides correction of localised tilt errors, there is a need to correct the global tilt in the wavefront responsible for continuous and random angular beam displacements. A jitter or wander correction system comprising of a tip-tilt mirror, tilt sensor, and a controller compensate for these global tilt errors, thereby generating a stable spot in the target plane. The Adaptive Optics Technologies/ Systems Developed at LASTEC are as follows :

### Dynamic Co-alignment System

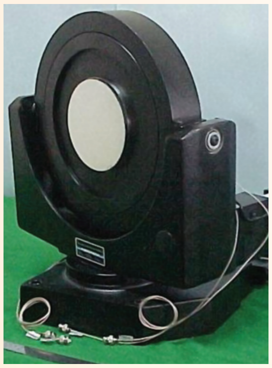
LASTEC has developed dynamic co-alignment system for real time correction of jitter for high power laser DEW systems. The system consists of two Fast

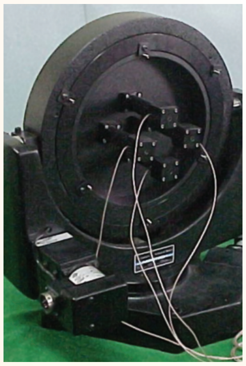
Steering Mirrors (FSMs) which move in tandem to correct the beam jitter while maintaining the optical axis of the beam. Tilt sensors are pyro-electric quadrant detectors which provide the required feedback for the closed loop operation of the system.

Dynamic Co-alignment System

### Fast Steering Mirror

The FSM designed and developed at LASTEC comprises of a 200 mm diameter and 5 mm thick mirror.



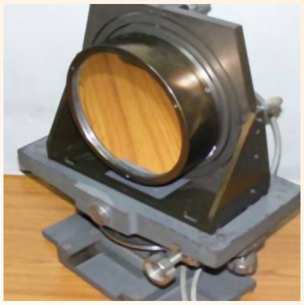


Front and Rear View of FSM

Four PZT stacked actuator move in push-pull mode to incorporate tilt along two orthogonal directions.

### Bimorph Deformable Mirror

The Bimorph Deformable Mirror (BDM) developed at LASTEC consists of silicon substrate firmly bonded to a piezo-ceramic disc. The front surface of the substrate is polished to optical quality and the back end is glued to separate piezo-discs in a specific pre-determined configuration. The size, shape and polarity of voltages applied to these piezo elements determine the type of aberrations that can be corrected by the deformable mirror.



Mounted and Exploded View of BDM

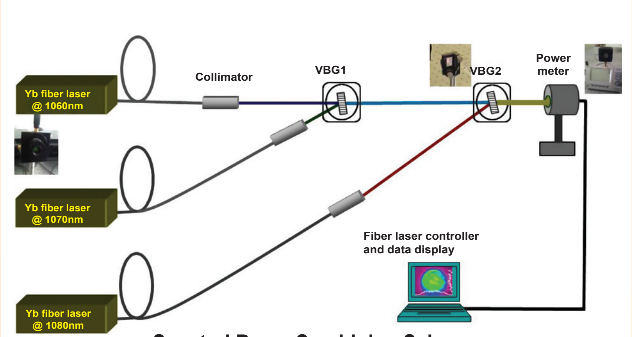
## Laser Beam Combining Technologies for High Power Lasers

Beam combining offers an alternative solution to obtain high power and high brightness laser radiation. Output beams of an array of lower power laser sources operating at moderate power can be combined by external optical elements, producing a single beam with increased power and brightness proportional to the number of lasers used. At LASTEC, the feasibility studies (under TASK-34) of different fiber laser beam combining technologies were carried out and the following technologies were identified for DEW applications.

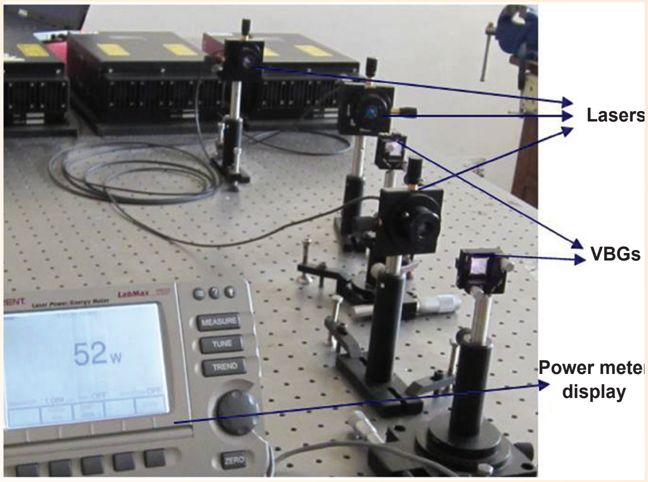
**Space Beam Combination:** This is incoherent beam combining approach in which a number of high power fiber laser beams are combined together, using one common beam director telescope. By this geometric beam coupling, a total laser power sufficient for an operational laser weapon system can be achieved. The individual beams from the different lasers are steered by servo-loops, using steering mirrors. This principle enables the concentration of total laser beam power at the common focal point on a distant target, also allowing fine tracking of target movements and first order compensation of turbulence effects on laser beam propagation. This technology is being persued for DEW systems at CHESS, Hyderabad. At LASTEC, the following technologies are being addressed for the development of Multi kilowatt fiber laser systems in association with industry or academia.

**Spectral Beam Combining (SBC):** This is incoherent beam combining approach in which beams from an array of lasers with each element operated at a different wavelength are combined into a single near diffraction limited beam using dispersive elements. This technique does not require frequency or phase matching of the sources, allowing for a stable and robust system. The brightness of the combined beam increases in proportion to the number of channels used. Surface gratings are the most widely used dispersive elements for SBC due to their good combining efficiency. To combine large number of channels with narrow spectral separation through surface gratings is difficult due to their limited dispersion capability.

Therefore for narrow spectral separation, Volume Bragg Gratings (VBGs) are used for beam combining of lasers with slightly shifted wavelengths. The VBGs have unique spectral response, i.e., their diffraction efficiency is close to unity when the Bragg condition is satisfied and is close to zero at other wavelengths. They have excellent thermal, mechanical and chemical stability. The availability of high damage threshold diffraction gratings and narrow line width fiber lasers are the major bottlenecks for the development of multikilowatt fiber laser systems using this technology. The near Gaussian beam quality and high system efficiencies are the merits of this technology.



Spectral Beam Combining Scheme



Set-up Using Two Volume Bragg Gratings

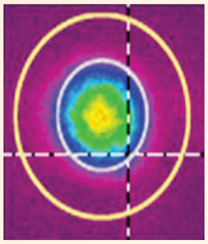
**Coherent Beam Combination (CBC):** This technology requires the phase matching of laser beams from different laser sources using phase locked loops. As the number of lasers increases so does the complexity and stability of the system. In this approach the brightness of the combined source is proportional to the square of the number of lasers used. The combined beam is highly coherent and polarized. This is mainly useful for spectroscopic applications. This is a viable approach for high power fiber laser systems and is being pursued in association with academia.

**Tapered Fiber Bundling (TFB):** This is an all fiber fusion spliced approach for combining the multiple fiber laser sources for development of compact and alignment free technology. The contrast of the output radiation of the tapered fibers is determined mostly by the mode coupling that inevitably exists in non-regular waveguides. The mode coupling effect leads to the transfer of part of the fundamental mode power to higher-order modes. Since the power remains in the core, it does not increase losses, however, it leads to degradation of the beam quality. The moderate beam quality of the combined beam is the major bottleneck of this technology and a lot of research is required for perfect tapering of the fiber bundles.

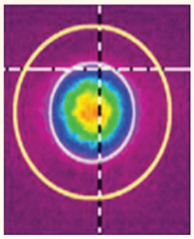
## Development of Continuous Wave, Single Mode Spectral Beam Combined Fiber Laser Source

At LASTEC, a 52 W continuous wave, single mode beam combined fiber laser source, based on spectral beam combining has been designed and developed. Three 20 W fiber laser beams were combined using two custom designed VBGs with combining efficiency of 90 per cent in terms of power and about 92 per cent in terms of overlapping beam diameters in the far field. Lasers are tested for their powers, beam profiles, and spectral linewidths.

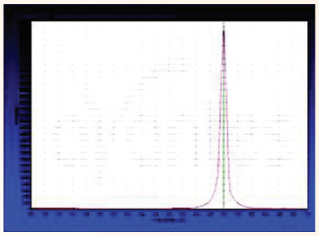
VBGs are experimentally tested for their diffraction efficiencies at different laser powers. Diffraction efficiency of VBG @ 1070 nm is 99 per cent. Recently LASTEC have scaled up the system and demonstrated the combined power of about 116 W using spectral beam combining with high beam quality.



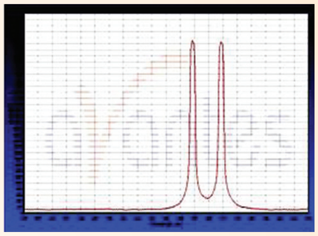
Single Beam Dia: 0.65 mm



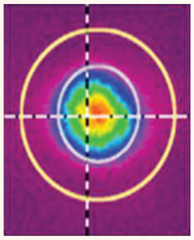
Double Beam Dia: 0.67 mm



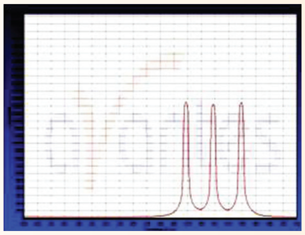
Single Beam



Double Beam



Three Combined Beams Dia: 0.70 mm



Three Beams

Experimental Set-up and Recorded Spectrums of Single and Combined Laser Beams

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