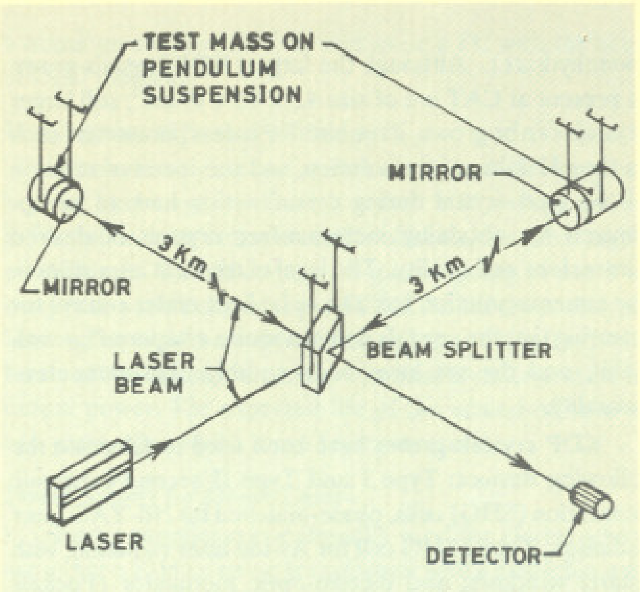
of upto 10^{-22}. Then there is a significant chance of detecting gravitational waves.

Because of this realization several such detectors have been planned. In USA a pair of 4 km arm length detectors are planned. Groups in UK and Germany are planning a 3 km arm length detector and groups in France and Italy are also working on similar plans. Australia is planning to set up an International Gravitational Observatory (AIGO) near Perth jointly with India and Argentina. The Indian participation in the project, the construction for which is expected to commence in 1996 will be in two areas, viz. i) data processing where Inter University Centre for Astronomy and Astrophysics (IUCAA), Pune will collaborate; and ii) in the design, fabrication and installation of the vacuum system, where CAT will participate. The UHV vacuum system will involve fabrication of two 3 km long and 1.22 m diameter vacuum tubes with minimum demountable joints and a large vacuum tank holding beam splitter etc.. The vacuum system is expected to cost nearly 20 million Australian dollars which is roughly one fifth of the estimated cost of the project.

An international workshop on 'New Technologies for Gravitional Astronomy' was organised by University of Western Australia, at Perth, from April 26-29, 1993 to review the construction of AIGO and exchange ideas. Shri A S Raja Rao from CAT was invited to the workshop and presented the details of a vacuum system configuration for AIGO.



Schematic of Interferometric GW Detector

Copper Vapour Laser Developed at CAT

Introduction

Copper vapour laser (CVL) emits light in the visible part of the spectrum at wavelengths 511 & 578 nm, and is the most efficient laser in this part of the spectrum. In this laser, first demonstrated by Walter et al in 1966, transient inversion is achieved by excitation of a resonance upper laser level from ground state level. Of the many metal vapour lasers that have been operated covering wavelengths from ultra-violet to infra-red, CVL has received the maximum attention because of its potential use in laser isotope separation. CVL is used for pumping high repetition rate tunable dye lasers which are ultimately used for selective excitation and ionization of desired isotopic species.

The lasing medium is copper in the atomic form. Vapours of copper are generated either by heating metallic copper to high temperature (1400-1600 °C) or by using salts of copper so that operating temperature is brought down considerably (400-600°C). There has been a considerable technological development, and average power of a single CVL has increased from 20 mW in 1966 to more than 100 W in 1993. Further increase in average power has been achieved by arranging these single lasers in master oscillator-power amplifier configuration. In this scheme the master oscillator is suitably improvised to provide a low power, good quality beam, and the power of the laser beam is increased by subsequent passage through a series of amplifiers in a specified time sequence. We discuss here some technological problems in the development of CVL and summarise our efforts and successes in that direction.

The operating principle of CVL can be best understood with reference to Fig.1, which shows the low lying levels of copper atom. Ground state of copper atom $^2S_{1/2}$ has the configuration $3d^{10}$ 4s. Promoting the outermost 4s elecron to higher orbitals i.e. 4p, 5p, etc. results in a series of ^2P levels which are connected to ground state by strong resonance transition. The first set of transitions from these resonance levels (with electron configuration $3d^{10}$ 4p) have wavelength 325 and 328 nm. There exists a configuration $3d^9 4s^2$ which is 1.5 eV above the ground state and is below the first resonance level. This configuration ($3d^9 4s^2$) gives rise to $^2D_{5/2}$ and $^2D_{3/2}$ levels and these are metastable because the radiative transition is forbidden by the parity rule of electric dipole transition. The free copper atom in ^2P levels has a finite probability ($2x10^6 sec^{-1}$) for decay to ^2D levels. Because the lower laser levels ^2D are metastable levels and can decay to ground level only via non-radiative decay (which is a slow process), the lower levels population

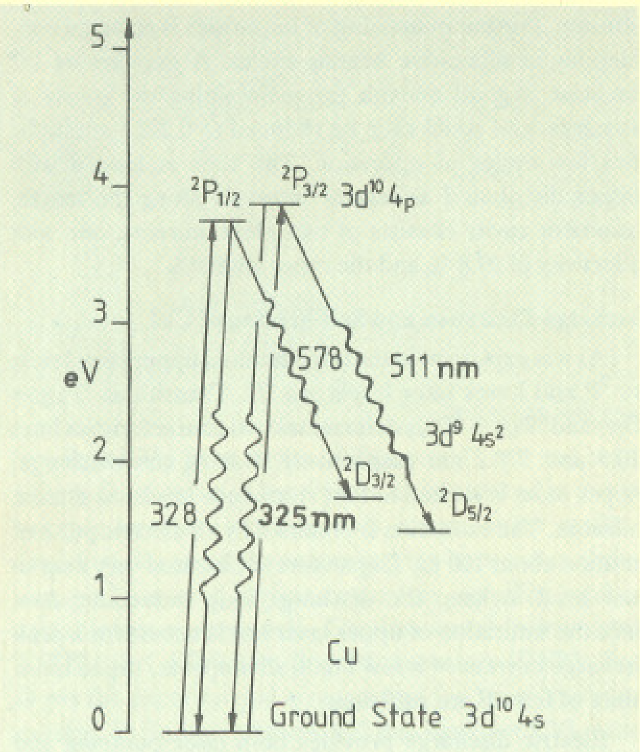


Fig.1: Low-lying levels of neutral copper atom

increases due to lasing resulting in self-termination of the laser. It is therefore necessary to wait until the population of the lower laser level has been reduced, before the next excitation pulse can be applied. Typical life time of the lower laser level is 100 - 200μs and thus the CVL is operated at 5 - 10 kHz repetition rate.

The copper atom in ^{2}P level has a rapid decay (lifetime 7 ns) to the ground state, but the atom density of copper can be so selected in a CVL that 325 and 328 nm transitions are subjected to strong radiation trapping. Thus the decay of ^{2}P levels directly to ground state level ^{2}S does not represent a significant loss. The e^- collisional excitation cross section to the first resonance levels is about an order of magnitude higher than the e^- excitation cross section to ^{2}D levels and an excitation from the ground state produces population inversion between ^{2}P and ^{2}D levels. Because of the small inversion time, excitation to the ^{2}P levels requires a short excitation pulse of typical duration 100 ns. Since the desired excitation of ^{2}P upper laser levels of copper provides the largest inelastic collision cross section for electrons and dominates all other electron loss processes, the CVL is an efficient laser and its efficiency is an order of magnitude higher than that of Argon ion laser. CVL with wall-plug efficiency of about 1% are commercially available.

Technological Development of CVL

The mainstream of CVL development worldwide has been with elemental copper laser. The first CVL had used an external oven to heat metallic copper upto the working temperature of 1500°C. Helium at few torr pressure was used as a buffer gas. The laser output was 24 μJ/pulse with an efficiency of 0.1 %.

The next major development in CVL was reported by Soviet workers Isaev et.al. in 1972. The discharge tube was surrounded by a thick layer of heat insulating material and the excess discharge energy itself was used to heat the copper upto the required temperature. This eliminated the need of an external heater and associated problems of material compatibility. The laser was operated giving 15 W of average power with 1% wall-plug efficiency.

It was presumed earlier that the relaxation mechanism of ^{2}D levels are via diffusion to the tube walls. A CVL was operated by Smilansky in Israel in a tube of large bore with Neon buffer gas at a pressure of 100 torr. Operation of CVL at such high pressure indicates that the relaxation of metastable levels could be achieved by super-elastic collision of electrons with atoms in ^{2}D state during the interpulse period. With the knowledge that at high buffer gas pressure the deactivation of metastable states by collision with the tube wall becomes less significant, Lawrence Livermore National Laboratory operated in 1983 an 80 mm diameter plasma tube with extractable power of 200 W per laser.

Our Development Efforts

The first CVL using externally heated oven was operated in 1983 at BARC giving 500 mW of average power at 500 Hz. The first self heating design of CVL was operated in 1985 giving about 15 W of average output power at 5000 Hz. Over the years our R&D efforts at CAT have optimised the heat insulating material used, the discharge tube diameter, the buffer gas parameters, and have improved the electronics for the excitation pulse. We now have standard versions of CVL that we describe below. The output beam of the CVL has a high divergence (2 mrad). Using unstable resonators we have improved the divergence to within a few times the diffraction limit.

The CVLs developed at CAT have specifications tabulated below and use neon as buffer gas. The gas flow rate is

Table I

	Model I	Model II
Beam diameter	25 mm	47 mm
Average output power	25 W	40 W
Pulse width	30 ns	50 ns
Repetition rate	5-12 kHz	4-6 kHz
Peak power	200 kW	150 kW
Input power	3.5 kW	4.5 kW
Efficiency	0.7 %	0.9 %

0.5 atm.lit./hr. It takes about one hour for the system to warm up and another 45 minutes to reach stable output power.

We now give some details of specific developments that went into producing these CVLs.

Laser Head Design

The basic design of laser head is shown schematically in Fig.2. It comprises of a recrystalized alumina tube placed concentrically in a buttressed end pyrex glass pipe. The annular space between the alumina tube and the glass pipe is filled with heat insulating material. This design supports the alumina tube all along its length and sagging of alumina tube at high temperature was eliminated. Further, there is no restriction for the free expansion of alumina tube at high temperature, and mechanical stresses are minimum. Vacuum seals are formed on relatively cool glass envelope, and water cooled electrodes are directly connected with the glass envelope using O-rings. This glass envelope is placed in a water cooled steel jacket. One electrode is directly connected to the steel jacket, thus forming a return path for discharge current. This way discharge loop inductance is minimized for attaining a fast rising current pulse. At the other end, glass envelope protudes out of metal jacket and holds the second electrode. Glass extension itself acts as ceramic break for the high voltage pulse.

In this design the thermal insulation is in the same envelope as the discharge tube, and outgassing of the impurities can seriously degrade the performance of the laser. To reduce the amount of impurities flowing into the discharge region, buffer gas is released into the discharge region through one of the hollow electrodes and evacuated out through the other electrode. Since the impedance to gas flow offered by fibre-filled annular space is much more than offered by alumina tube, discharge region is being continuously flushed with buffer gas. Impurities from the surroundings will reach the discharge region only through diffusion. Further outgassing of impurities is reduced considerably in successive heating cycles. A gas flow of 1-2 atm.lit/hr is good enough for maintaining the purity of discharge, and could even be reduced to 0.2-0.5 atm.lit/hr after few cycles of operation. The tube is loaded with copper distributed at regular intervals along the length. Resonator cavity consists of two plane mirrors, one with reflectivity of 99.8 % and the other with 8%.

Discharge Excitation and Self-heating of CVL

As was explained in the introduction, upper laser levels are ^2P and lower laser levels are ^2D. Transitions $^2P_{3/2} \rightarrow {}^2D_{5/2}$ and $^2P_{1/2} \rightarrow {}^2D_{3/2}$ determines two characteristics lines 510.5 and 578.2 nm respectively. During the discharge, copper atom is excited to first resonance levels via e-atom collisions. The excitation is obtained by an electric pulse of duration about 100 ns. Capacitors are located very near to laser head to keep the discharge loop inductance low. Since the saturation of upper laser levels occurs for a peak discharge current of a few hundred amperes, capacitance values of few nF are sufficient.

Electric discharge provides both laser pumping and thermal heating. Thermal conductivity of heat insulation is chosen so that input power does not raise the temperature of gas to more than the upper limit of 3500K, decided by the thermal population of the lower laser levels. Optimum power loading is more important in the case of large diameter discharge tubes because the gas near the axis of plasma tube is not in good thermal contact with the wall.

Improvement in Beam Quality

The high average power from a CVL can be utilized efficiently if the divergence of the beam is very low. The minimum divergence of a beam depends on its wavelength λ and diameter D, and is given by its diffraction limit [2.44 λ/D]. The divergence from a CVL with a plane-plane resonator is proportional to the diameter to length ratio of active medium and can be as high as 200 times the diffrac-

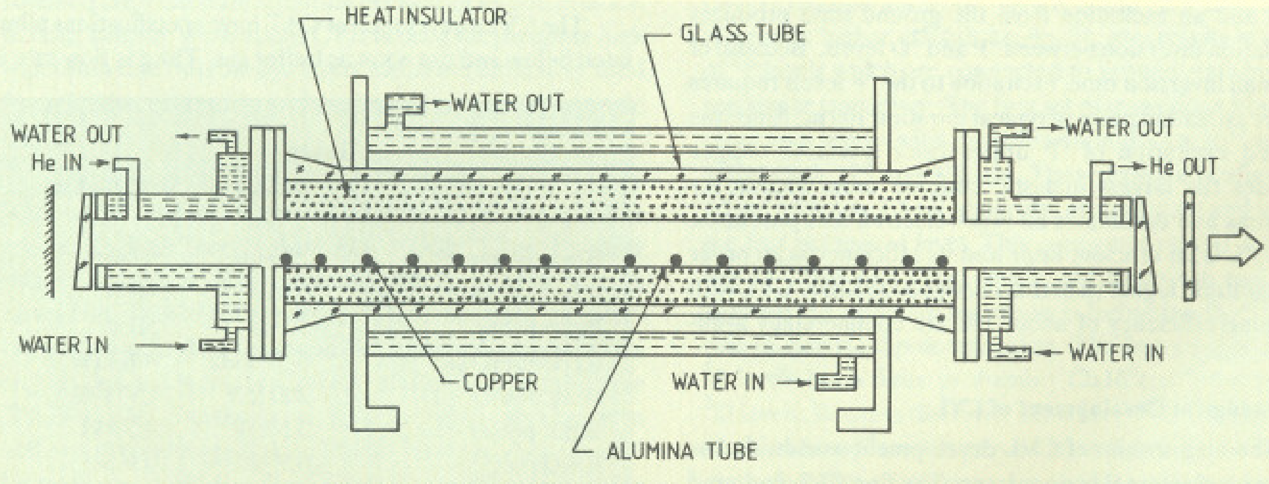
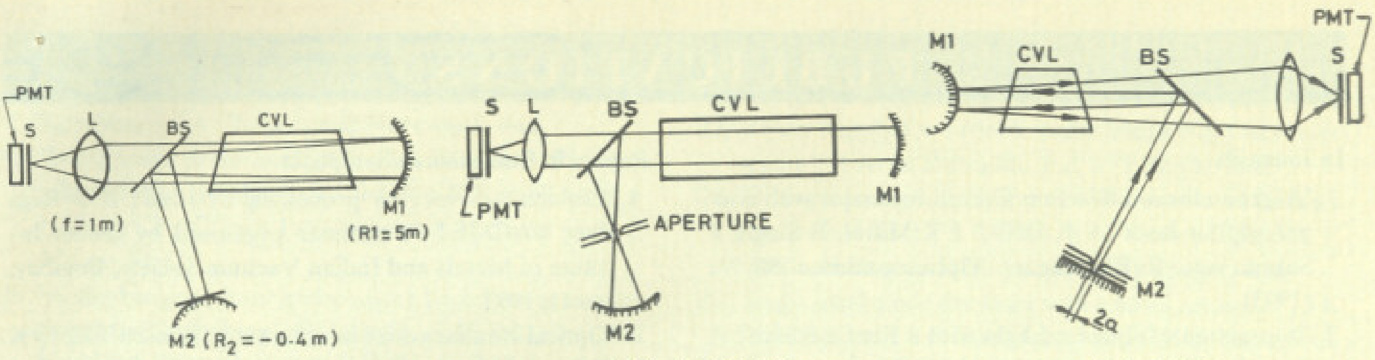


Fig.2: Schematic of laser head with electrodes at tube ends



(a) PBUR (b) NBSFUR (c) DFR

Fig.3: Resonators used for improving beam quality

tion limit [DL] from a tube of diameter 47 mm and length 150 cm. Divergence of laser beam can be reduced by putting suitable aperture so that only lowest order mode is amplified. To avoid the accompanying laser power reduction, we have used various resonators including confocal unstable resonators, self- filtering unstable resonators [SFUR] and diffraction filtered resonators [DFR]. Fig 3 shows the experimental arrangement for 3 such resonator systems. In fig.3(a) we show a 25 mm diameter CVL with a confocal positive branch unstable resonator [PBUR] of magnification 12.5. The PBUR uses concave and convex mirrors of focal lengths 2.5 m and 0.2 m respectively, separated by the difference of their focal lengths. The output was taken out from a partially transmitting mirror in folded resonator geometry. An output of divergence 0.4 mrad (against the original 2 mrad) with an average power of 7 W is obtained.

In self- filtering unstable resonators, a hard aperture of specific size is inserted at a location where it spatially filters its own diffraction pattern. Fig 3(b) shows a CVL with a confocal negative branch SFUR. It is formed by concave mirrors M_1, M_2 of focal lengths f_1, f_2 of 1.5 m and 0.13 m respectively, separated by 1.63 m and with an aperture of diameter 0.4 mm at confocal plane. The diameter of aperture is equal to $2x(0.61\,\lambda f_2)^{0.5}$. The aperture allows only the central lobe of the diffraction pattern to pass through it and in this process generates a diffraction limited beam of very smooth intensity distribution. The measured divergence in this set up was 2 times DL. Inserting a self filtering aperture close to convex mirror in confocal PBUR described earlier, the divergence reduces to the DL. The laser power also reduces from 7 W to 0.5 W.

To increase the power in the diffraction limited beam, a resonator based on the diffraction by one intracavity aperture and the spatial filtering in the far field by another intracavity aperture is used with CVL. This resonator is known as diffraction filtered resonator [DFR]. Fig 3(c) shows a CVL with a DFR formed by a convex mirror of focal length 0.2 m and a plane mirror separated by 2.3 m, containing an aperture of diameter 0.4 mm at plane mirror. With this set up a 25 mm beam of 2 W average power with 0.1 mrad divergence is obtained. This divergence corresponds to 2 times DL.

Future Outlook

The main technological problem in the development of CVL was associated with the high working temperature of the discharge tube. There have been parallel efforts to reduce the working temperature to 500-600 °C range by using copper salts (usually copper halides). Free copper atoms are generated by dissociation, by using pulsed discharge in a pair – the first to dissociate the halide, and the second to produce the lasing – with proper time delay. A group in UK used hydrogen bromide gas along with Neon buffer gas for insitu preparation of copper bromide and reported a significantly higher efficiency of better than 3 % (c f ~1% with metallic copper) obtaining laser power in excess of 100 W. Long term reliable operation at high input power of CVL using copper halides presents some technological problems such as discharge instability and regulation of tube temperature.

The main use of CVL so far is in pumping tunable dye lasers. Because of their short pulse duration and high repetition rate operation, these lasers might also be competing with CO_2, Nd-YAG or excimer lasers in the field of material processing. CVL being in visible region can be transported upto the work place using readily available optical fibres, and this makes it a promising laser for material processing in comparatively inaccessible areas.

Another promising application of this laser is in forensic science. Results of this laser in the use of fingerprint detection are comparable to those of the currently used Argon ion laser. CVL also has applications in high speed photography and medical science.

J K Mittal and S K Dixit