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Design and performance of a 20 watt copper vapour laser

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Abstract. The design of a simple discharge-heated copper vapour laser (DHCVL) is presented and its output characteristics studied. An auxiliary power supply is used to precondition the discharge tube so as to eliminate the possibility of thyratron damage. The laser gives an average power of 20 W at a repetition rate of 6 kHz. Helium was used as the buffer gas.

1. Introduction

The copper vapour laser (CVL) is an excellent source for pumping dye lasers of high repetition rate (Hargrove and Kan 1980). The design of a CVL, however, poses several technological problems due to high operating temperatures (1600–1900 K), low pressure and high-voltage fast discharges. Various CVL designs, incorporating external heating (Piltch and Gould 1966, Kim and Convey 1982, Gabay *et al* 1982, Singh *et al* 1984), self-heating (Smilansky *et al* 1978) and a sealed-off tube (Alger and Bennett 1982, Marazov *et al* 1984) have been reported in the literature. Externally heated designs, though good for parametric studies, suffer from frequent heater failure. Discharge-heated lasers, on the other hand, use excess discharge energy itself to heat copper. In these lasers the discharge tube is of recrystallised alumina. Various materials such as refractory metal foil (Alger and Bennett 1982), alumina and zirconia fibres (Kim and Convey 1982) and graphite felt (Singh *et al* 1984) have been used as thermal insulation.

The CVL comes from a class of self-terminating lasers (Bridges 1979), which require fast excitation. Most designs provide a coaxial current return path, through the metal housing itself, in order to reduce system inductance. In these designs, the high-voltage electrode is separated from the housing by a ceramic-to-metal joint commonly referred to as a ceramic break. This ceramic break is expensive and fragile. Singh *et al* (1984), in their design, have extended the alumina discharge tube itself out of the vacuum jacket to dispense with the ceramic break. Alger and Bennett (1982) have used two alumina tubes in their system, one for containing the discharge and other as the vacuum chamber. The design has high resistance to thermal shock but lacks simplicity.

The high-voltage discharge in the CVL is initiated by a thyratron switch, which is the most expensive and critical component of the system. The life of this switch depends on the impedance offered by the discharge. Since the discharge impedance at start-up is much higher than that under normal operating conditions, the switch is subjected to increased stress. The increase in this impedance is due to outgassing of impurities from the components used in constructing the laser. It also depends on the presence or absence of the metal vapours. Ideally the thyratron should be put into operation

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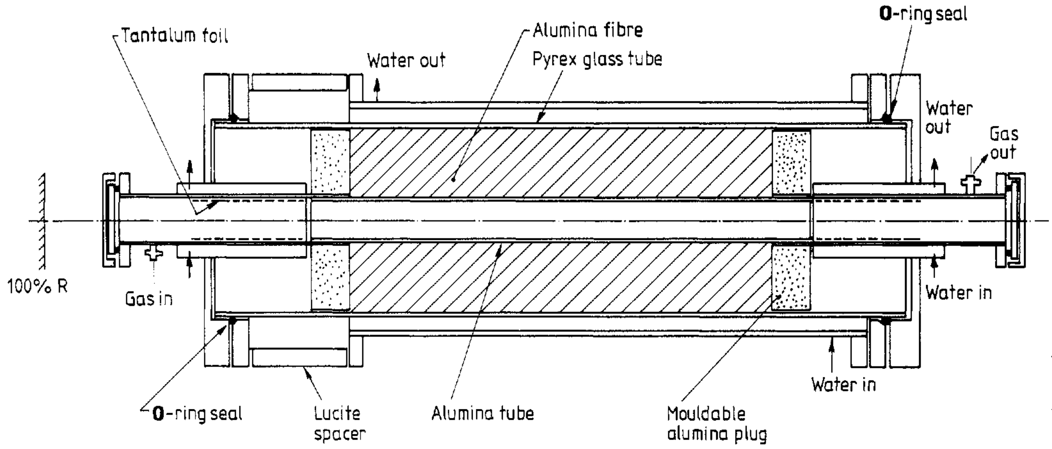

Figure 1. Schematic diagram of the discharge tube of the copper vapour laser.

after the tube is degassed and the operating temperature is reached. Manufacturers of commercial CVLs either use an extra inductor to slow down the discharge current pulse during set-up runs or use a DC discharge to heat the tube to the operating temperature before the thyratron is put into operation. This reduces unnecessary loading of the thyratron.

In this paper we discuss the design of a discharge-heated CVL which eliminates the need for the ceramic break. A new method of AC discharge heating to remove outgassed impurities from a freshly assembled tube is demonstrated. This supply is later used to heat the tube to operating temperature before enabling the thyratron for the pulsed discharge.

2. Laser head design

The discharge tube consists of a recrystallised alumina tube (25 mm ID, 1.2 m long) placed concentrically in a Pyrex glass vacuum envelope (100 mm ID, 1.5 m long) with the help of end plugs (figure 1). The plugs, made of mouldable alumina (SALI mouldable, Zircar product), are pre-fired at 1500 K to remove moisture. The annular space between the alumina and the glass tubes is filled with alumina bulk fibre (type ALBF 1, Zircar product) at a packing density of $2.0\text{–}2.5 \times 10^2\ \mathrm{kg\ m^{-3}}$. This eliminates the problem of sagging encountered in some designs (Smilansky *et al* 1978). The glass vacuum envelope was then placed in a water-cooled stainless steel jacket. The jacket has a flange at one end, mounted on insulating spacers, to support the cathode. Unlike the designs using a ceramic break the volume between the glass vacuum envelope and the jacket was not evacuated. Water-cooled stainless steel electrodes inserted from the two ends seal the glass tube with the help of neoprene **O** rings. The electrodes have provision for mounting windows, either normal to the discharge axis or at Brewster's angle. A lining of perforated tantalum foil in the electrodes ensures that the discharge terminates within it.

The thermal insulation in this assembly is in the same vacuum envelope as the discharge tube. Outgassing of the impurities can therefore seriously degrade the performance of the laser. To reduce the amount of impurities flowing into the discharge region, buffer gas was released into the discharge tube through the cathode and was evacuated out through the anode. Since the impedance to the gas flow offered by the fibre-filled annular space is higher than that offered by the alumina tube, impurities reach the discharge region only through diffusion. These were continuously removed by flowing helium at the rate of $2\ \mathrm{l\ atm\ h^{-1}}$. Outgassing of impurities is considerably reduced in successive heating cycles.

The tube was loaded with about 60 g of OFHC copper, distributed at regular intervals along the length. The resonator cavity consisted of two plane mirrors, one with a reflectivity of 99.8% and the other of 8%, separated by about 1.9 m.

3. Power conditioning system

The copper vapour laser is a resonantly charged thyratron-switched discharge device. Figure 2 shows the modulator circuit with the component values used in our laser. The switching device – a hydrogen thyratron – is the most critical component of the system and its life is severly affected by the behaviour of the discharge tube. The operation of the modulator circuit is highly detrimental to the thyratron at the beginning of the set-up runs when the newly assembled laser tube offers quite a high discharge impedance. This is due to the large amount of impurities like oxygen and water vapour which are outgassed during heating. Oxygen and water vapour are electronegative and so attach free electrons from the discharge to form negative ions (Cobine 1941). The formation of negative ions in the discharge restricts the growth of the discharge current, thus offering high impedance (Papoular 1965). Under normal operating conditions C_1 is charged resonantly to approximately twice the DC supply voltage through the bypass resistance R. Once C_1 is charged, the charging current from the supply reduces to zero. The diode D prevents C_1 from discharging back into the power supply. Triggering of the thyratron now initiates the charging of C_2 from C_1. The capacitor C_2 is charged until the gas in the discharge tube breaks down. The DC breakdown voltage under normal operating gas pressure and electrode separation is much lower than the voltage required for efficient pumping of the laser. It is possible, however, to reach higher breakdown voltage if the voltage rise time is comparable to the formative time lag of the discharge (Meek and Craggs 1978). Voltage rise times in thyratron-switched CVL systems are

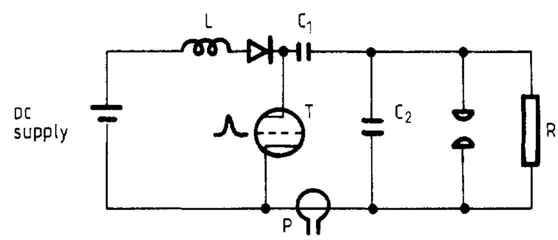

Figure 2. Diagram of the modulator circuit. $C_1 = 6$ nF., $C_2 = 4$ nF, $R = 1.5\ \mathrm{k\Omega}$, $L = 200$ mH, $T = C \times 1535$ (EEV), P = current probe.

typically 100–200 ns. On breakdown, the capacitor C_2 discharges into the tube, giving rise to lasing action. It should be noted that the discharge tube impedance under normal conditions is low enough that the discharge time of C_2 is less than its charging time. The freshly assembled tube offers high discharge impedance. This results in a longer discharge time for C_2 (i.e. its discharge time is greater than the charging time). The thyratron can conduct in the reverse direction in arc mode due to high inverse voltage. Most of the energy from C_2 will go back into C_1. High reverse voltage and current through the thyratron are known to severely reduce its life (English Electric Valve Co. 1972). Prolonged operation under these conditions may damage the thyratron irreversibly due to arc formation. Also the energy coupling to the discharge reduces as most of the energy is dissipated either in the bypass resistance or in the thyratron itself. It is therefore necessary to avoid loading of the thyratron during setting-up runs and start-up time. High inverse voltages can be reduced by introducing an extra inductor between C_1 and C_2 during setting-up runs. This slows down the charging of C_2.

The risk of thyratron damage can be eliminated if it is not used during set-up and starting runs of the laser. M/s Quantron (Australia) use a switched-mode power supply for the modulator in their laser. This has provision for applying a DC discharge with thyratron disabled, until the required temperature is reached. The thyratron is then enabled for pulsed operation. Although this technique is attractive, the design of a high-voltage switched-mode power supply for CVL is complicated and details are not available in the literature. AC discharge heating, on the other hand, can provide a simple inexpensive alternative. We have used an auxiliary supply to heat the tube by an AC discharge during set-up runs. The pulse modulator circuit was disconnected and a power transformer of 3 kV, 1 A, 50 Hz rating was connected across the electrodes of the discharge tube. An inductor was connected in series with the discharge tube to limit the current.

The discharge impedance can be estimated by measuring the current in the discharge loop. The change in the magnitude of the current before and after heating can give an idea of the change in impedance due to the cleaning up of the discharge tube. A current probe (Tektronix CT-5 and 6015) was introduced at point P as shown in figure 2. The peaking capacitor C_2 was removed and the modulator circuit enabled. The current pulse was displayed on an oscilloscope (Tektronix 7834). Figure 3(a) shows the discharge current in a freshly assembled tube under cold conditions. The current reaches a peak value of 14 A at a charging voltage of 15 kV and has a long exponential decay. If the inductance associated with the bypass resistance is neglected the effective load as seen by the circuit is equal to a parallel combination of discharge impedance and the bypass resistor R. For a bypass resistor of 1.5 kΩ, the actual current through the discharge is only 4 A. Most of the energy is dissipated in the resistor and energy coupling to the discharge is poor. The pulsed discharge was disabled and the auxiliary heating supply was connected across the discharge electrodes. The tube was heated to about 1600 K for about an hour. Helium flowed through the tube at the rate of 10 l atm h^{-1} to remove the impurities. The auxiliary supply was then disconnected and the tube allowed to cool. The pulse discharge was then enabled. Figure 3(b) shows the discharge current with C_2 removed. The pulse has a duration of about 2 μs at the base. The discharge current has now increased to 14 A, indicating that its impedance is considerably reduced and the tube has less outgassed impurities. The tube was subjected to several AC discharge heating and cooling cycles under a constant flow of helium, after which it was loaded with copper. Figure 3(c) shows the discharge current under normal lasing conditions, i.e. with C_2 reconnected in the circuit. The peak current is about 800 A.

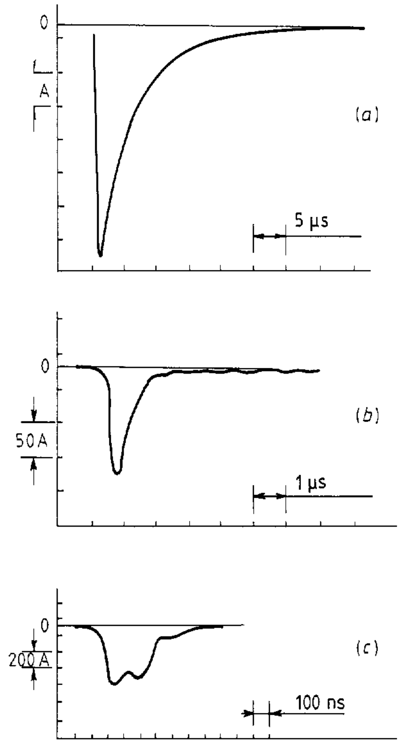

Figure 3. Discharge current: (a) cold conditions, newly assembled tube, C_2 removed; (b) cold conditions after AC heating, C_2 removed; (c) under lasing conditions, C_2 reconnected..

4. Laser performance

The discharge voltage, current and the laser pulses are shown in figure 4. The voltage was monitored with a high-voltage probe (Tektronix 6015) and the current by Tektronix CT-5 and 6015 probes. The laser pulse was detected by a biplaner vacuum photodiode (Hamatsu R 1193-UO2). All the pulses were displayed on a storage oscilloscope (Tektronix 7834). It is seen that the voltage pulse reaches its peak value in about 100 ns. As the breakdown occurs the current builds up with a rise time less than 100 ns. The laser pulse appears during the rise of the current pulse and has a FWHM of 40 ns. It is noticed that the laser pulse builds up when the voltage is at the peak, thus providing a high $E/\sqrt{Nn}$ value, E, N and n being the electric field and the number densities of the buffer gas and the copper vapour respectively. This ensures efficient excitation of the upper laser level (Manatsakanyan et al 1978).

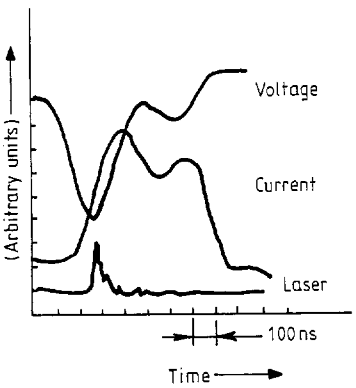

Figure 4. Discharge voltage, current and laser pulses.

The average output power was measured with a power meter (Coherent 210) after sampling the output beam with a partially reflecting glass plate. Figure 5(a) shows the variation of laser power as a function of helium pressure. The power decreases from about 16.5 W (5 kHz) at 0.5 kPa to about 11.5 W (5 kHz) at 2 kPa. No measurements were carried out at pressures below 0.5 kPa because it results in significant diffusion and deposition of vapours on the windows. The variation of output power with discharge voltage is shown in figure 6(a). The power was also measured as a function of pulse repetition rate (figure 7). The output power increases from about 15 W at 5 kHz to about 20 W at 6 kHz.

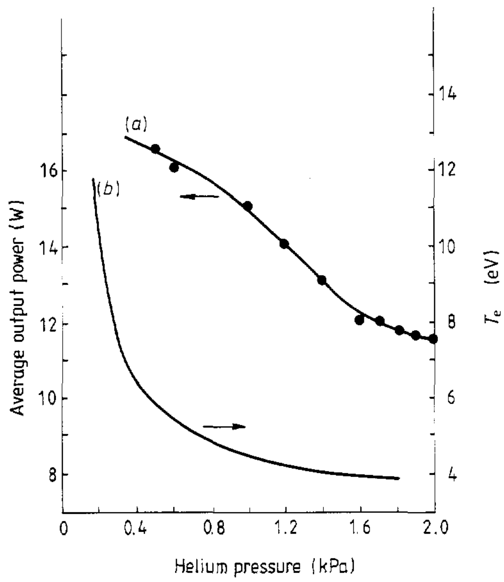

Figure 5. (a) Variation of laser power with helium pressure. (b) Estimated peak electron temperature T_e (Kushner 1981). Voltage = 13 kV, pulse repetition rate = 5 kHz, C_l = 6 nF.

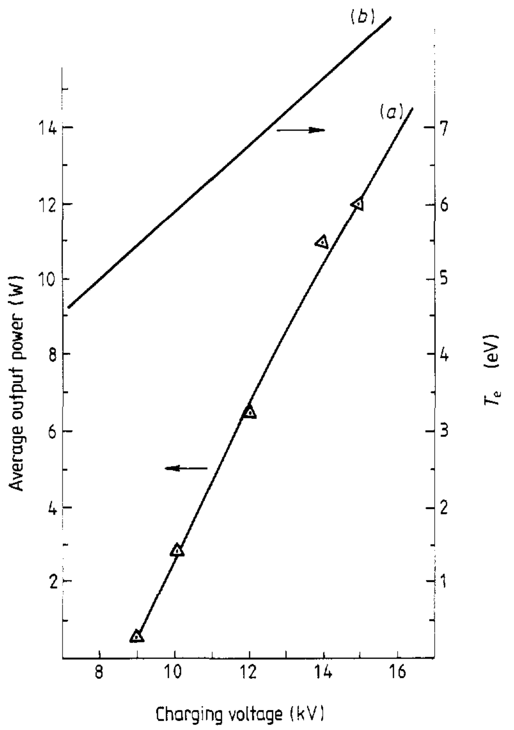

Figure 6. (a) Variation of laser power with charging voltage. (b) Estimated peak electron temperature T_e (Kushner 1981). Helium pressure = 1.2 kPa, pulse repetition rate = 5 kHz, C_l = 6 nF.

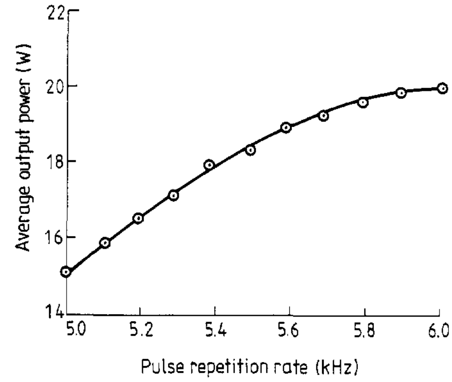

Figure 7. Variation of output power with pulse repetition rate. Voltage = 15 kV, helium pressure = 1 kPa, C_l = 6 nF.

The peak electron temperature T_e for the system was estimated using Kushner's (1981) analysis. The variation of T_e with helium pressure and discharge voltage for the region of interest is shown in figures 5(b) and 6(b) respectively. T_e decreases from about 10 eV at a helium pressure of 0.2–0.3 kPa to about 4 eV at 1.8 kPa. According to Kushner (1981) the optimum peak electron temperature is in the range 4–10 eV. Below a T_e of 4 eV the output power decreases due to dominant excitation of the lower laser level. For $T_e > 10$ eV excitation of states higher than the upper laser level dominates. The average output power decreases as the helium pressure is increased because T_e falls to about 4 eV at 1 kPa pressure (figure 5(b)). The output power approaches saturation around 0.4 kPa where T_e is about 6.5 eV. The dependence of output power on discharge voltage (figure 6(a)) and the corresponding estimated values of T_e (figure 6(b)) indicate scope for increasing the output power is the charging voltage if increased beyond 15 kV.

The laser pulses at 510.6 nm and 578.2 nm were recorded after separating the two components by suitable filters. The emission at 578.2 nm was delayed by about 20 ns with respect to the 510.6 nm emission (figure 8). This delay, reported by Kim and Kiegon (1985), was found to be a function of gas pressure. The delay of 20 ns at 1.5 kPa helium pressure

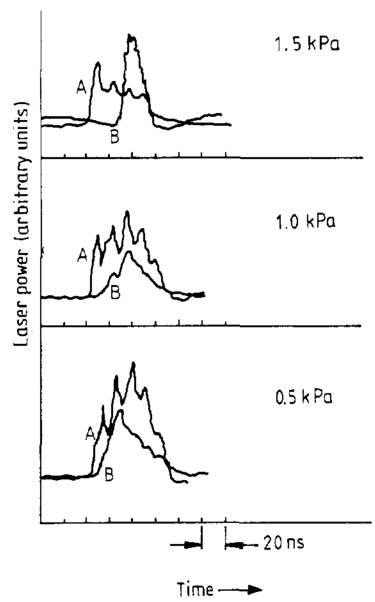

Figure 8. Variation of delay between 510.6 nm (A) and 578.2 nm (B) pulses with helium pressure.

reduced to about 5 ns at a pressure of 0.5 kPa. Kniepp (1980) has calculated the pump functions for the two transitions at 510.6 nm and 578.2 nm using rate equations for the upper and lower laser levels. It is shown that the pump function for the 578.2 nm reaches its peak value at a time when the pump function for 510.6 nm reduces to zero, a delay in time of about 10 ns. This is attributed to a variation of electron temperature and distribution during the excitation pulse. The delay between the green and the yellow emission is important for the performance of CVL pumped Rhodamine 6G dye lasers, which emit at 569–608 nm. Detailed investigations, currently underway to study the behaviour of this delay, will be reported elsewhere.

An average output power of 20 W was obtained at an electrical input of 4 kW, giving an overall efficiency of 0.5%. The laser takes about 45 min to heat the tube to the operating temperature. The laser has so far clocked 150 h in about 25 heating cycles. No degradation of the discharge tube is observed.

In conclusion, a simple design of a CVL, giving an output of 20 W at 6 kHz, is described. Its output characteristics are discussed. An auxiliary power supply is used to preheat the discharge tube to remove impurities and to reduce the thyratron loading. The auxiliary supply is later used to obtain the operating temperatures before the pulsed discharge is initiated.

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