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Characteristics of a copper bromide laser with flowing Ne–HBr buffer gas

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The operating characteristics of a small self-heated copper halide laser (λ = 510.6 and 578.2 nm) are described, where the copper lasant atoms are produced by electric-discharge dissociation of copper bromide that is generated *in situ* by flowing Ne–HBr gas mixture over copper pieces in the laser tube. The excitation technique permits fast startup (< 1 min to laser oscillation from cold), and rapid and simple control of the CuBr vapour pressure, simultaneously introducing H_2 to increase the efficiency. Specific laser output energies and average powers of 12 μJ cm^{-3} and 195 mW cm^{-3}, respectively, are almost a factor of 2 higher than those previously reported in the literature for multi-kilohertz copper bromide lasers. A maximum power of 7.8 W was obtained from the 40 cm^3 active region. At its highest efficiency (0.8%) the laser produced 6.1 W.

1. Introduction

Copper halide lasers, which use cyclic transitions of atomic copper, continue to be of considerable interest. Their output characteristics are comparable with those of high temperature copper vapour lasers. Both high temperature and halide lasers are capable of producing specific output powers of 100 to 130 mW cm^{-3} at efficiencies of about 1% [1–5]. Copper vapour lasers generally produce maximum output powers at pulse repetition frequencies (p.r.f.s) of 4 to 12 kHz [5, 6] and can generate 8 to 12 μJ cm^{-3} per laser pulse [1, 2]. Copper halide lasers, on the other hand, usually operate at p.r.f.s of 15 to 21 kHz for maximum output power, but typically produce only 2 to 7 μJ cm^{-3} per pulse [3, 4, 7–11].

In contrast to copper vapour lasers, which operate at 1400 to 1600° C, the working temperatures of copper halide lasers are considerably lower at 400 to 600° C. These lower temperatures greatly simplify the construction of the laser tubes, for then fused silica cylinders with minimal insulation are sufficient to constrain the discharge region. In the case of the pure metal laser, the necessary vapour pressure of copper is established by using the waste heat of the pulsed discharge to heat the tube. The high temperatures required in the discharge region of the pure metal laser necessitate careful optimization of the tube insulation, with the need for a concentric construction with an inner alumina ceramic and outer quartz tube. Insulation, typically fibrous alumina, Saffil or zirconia felt, must be packed between the two concentric tubes to allow the required temperature in the active region to be attained. Furthermore, the high operating temperatures of pure copper laser systems dictate that startup times (from cold) are generally in the region of 60 to 90 min due

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to power limitations [12]. For copper halide lasers the low temperatures of operation enable laser tubes to be constructed wholly from quartz and with minimal insulation. The use of quartz readily permits the incorporation of side arms adjacent to the discharge region [7]. Placement of the solid copper halide into the side arms enables its vapour pressure (in the active region) to be adjusted independently of the tube temperature by means of an external heater. Due to the combination of low thermal mass and low operating temperature, the warm-up times of halide lasers are considerably shorter than those of their higher temperature counterparts. Even so, the thermal response time of the side arms can still be measured in minutes, and startup of the laser from cold is at best of the order of 5 to 10 min [13].

Recently the generation of copper salt *in situ* by the action of Br_2, Cl_2 [14] or HBr [15] flowed over copper segments in the laser tube was reported. This method of producing the copper salt obviates the need for side arms, as the vapour pressure of the copper halide is controlled by adjustment of the partial pressure of the Br_2, Cl_2 or HBr present in the laser tube. Bromine is a liquid at room temperature and, consequently, control of the amount of bromine vapour entrained in the flowing buffer gas is difficult. On the other hand, chlorine is a gas at room temperature, which allows simpler handling and metering [14]. Unfortunately, the use of chlorine instead of bromine leads to lower laser output powers [14, 16]. HBr offers the best characteristics of both bromine and chlorine, being able to donate bromine to the discharge and be metered as a gas at room temperature.

The use of HBr also has other advantages. First, it donates hydrogen to the active region. The addition of hydrogen in small quantities (40 to 65 Pa partial pressure) has been shown to increase significantly both the output power and the efficiency of copper bromide lasers [7, 9]. Second, the generation of the copper halide *in situ* by the reaction of HBr and copper enables high power (10 W) laser action to be obtained within 45 s from a cold startup [15]. No details regarding the efficiency or the characteristics of the copper bromide laser with flowing HBr–Ne were reported in [15]. In this paper we describe in detail for the first time the characteristics of a copper halide laser employing *in situ* generation of the copper salt by the action of HBr on copper metal in the tube.

2. Experimental apparatus

The active region of the laser tube was confined by an alumina tube with inside diameter 13 mm, outside diameter 17 mm and length 30 cm. A fused silica cylinder sleeved the alumina tube. Fixed by Viton O-rings at each end of the silica tube were stainless steel endflanges cut to Brewster's angle at the exit windows. The windows were of quartz, also sealed by Viton O-rings to the endflanges. The electrodes were hollow cylinders of molybdenum foil. The laser tube was thermally insulated with a thin (5 to 10 mm) layer of Saffil wrapped around the outside of the laser tube. The required insulation was established for a charging voltage of 12.5 kV and a p.r.f. of 16 kHz, corresponding to an input energy of 690 W. Provision was made for watercooling of the endflanges. Inlet and outlet vacuum connections were fitted to permit the buffer gas to be flowed through the tube at rates of 0.5 to 1 l atm h^{-1} (50 to 100 l kPa h^{-1}). Short pieces of high purity copper sheet (each folded to $10 \times 3 \times 1\,mm^3$; 99.99% purity) were placed along the floor of the alumina tube at intervals of 3 cm. The optical cavity comprised a flat 400 to 700 nm high-reflector (> 99.5%, Tec-Optics), and an uncoated quartz flat as the output coupler.

The laser tube was excited by a conventional resonant charging, capacitance transfer circuit. A storage capacitor of nominally 0.65 nF (0.55 nF at operating temperature) was

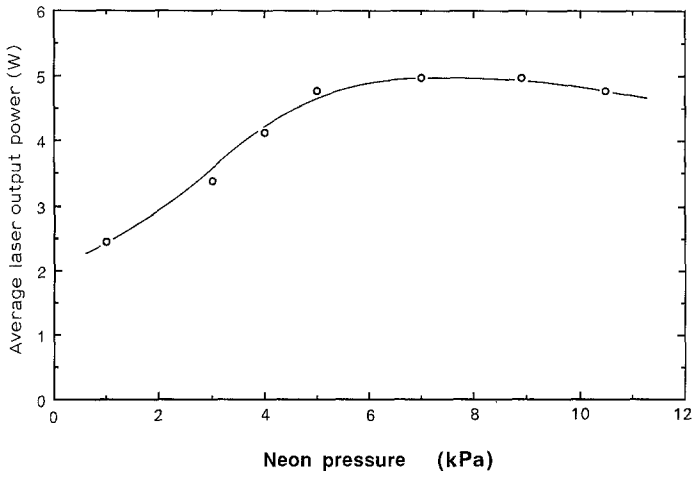

Figure 1 The variation of average laser output power with Ne buffer gas pressure: p.r.f. 16 kHz, voltage 12.5 kV, HBr presure optimized at each point.

charged to a maximum of 14 kV, and its energy switched by an EEV (English Electric Valve) thyratron type CX1535 at p.r.f.s of up to 30 kHz into a peaking capacitor (0.6 nF nominal value, 0.5 nF in operation) in parallel with the laser tube. A current return coaxial with the laser tube ensured current pulses of short risetimes. Current pulses of up to 300 A peak were generated, with typical risetimes of 40 to 60 ns.

3. Experimental results and discussion

3.1. The influence on laser operation of neon pressure

Initially, the dependence on the buffer gas pressure was determined. The charging voltage was set at 12.5 kV with a p.r.f. of 16 kHz, and the buffer gas flow rate was set at about 0.5 $1\,atm\,h^{-1}$ (50 $1\,kPa\,h^{-1}$). At each buffer gas pressure the HBr partial pressure was optimized. With the addition of a small amount of HBr, the sidelight spectrum changed from that of pure neon to display also transitions of copper. Laser action initially occurred within a narrow annular region near the tube wall. As the partial pressure of the HBr was increased, the inner radius of the annulus of laser radiation gradually decreased until eventually the intensity appeared uniform across the beam. This behaviour is typical also of conventional copper bromide lasers [17]. Turning off the HBr flow resulted in the output power falling to zero over about 30 s and the sidelight spectrum returning to that of neon.

The variation of the average laser output power with buffer gas pressure is presented in Fig. 1. At each Ne pressure the HBr pressure was set for maximum laser output power. The charging voltage was maintained constant at 12.5 kV, and the p.r.f. was 16 kHz. The output power initially rose quickly with increasing buffer gas pressure and reached a maximum between 6 and 9 kPa. Although not shown with the data in Fig. 1, increasing the operating pressure to 15 kPa caused the laser output power to fall by only 20% relative to that obtained at 7 kPa. The broad range of buffer gas pressures over which strong laser action occurred is similar to the behaviour of conventional copper bromide lasers [7, 18, 19]. However, we did not observe any of the discharge instabilities noted in [7] for pressures above 2 to 3 kPa or in [19] for pressures above 10.5 kPa. Such instabilities and contraction

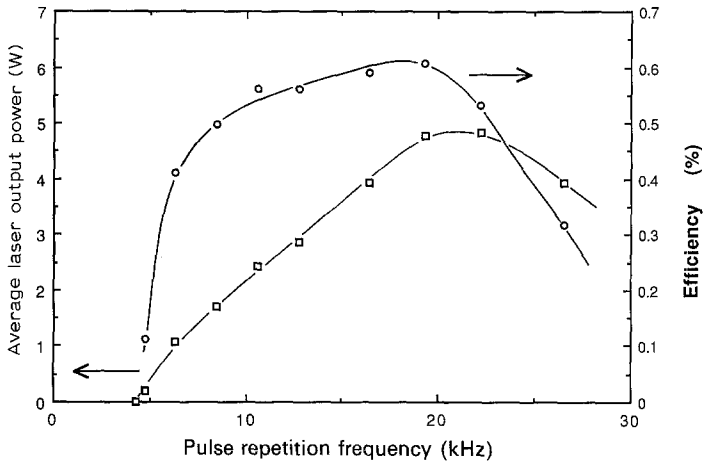

Figure 2 Average laser output power and laser efficiency (based on stored energy) as functions of p.r.f.: voltage 12.5 kV, Ne pressure 7 kPa, HBr pressure 125 Pa.

of the discharge are most likely to have been related to increased levels of Br (which is electronegative) in the discharge [20]. In our laser the ability to maintain the working concentration of Br at a level no higher than that required for maximum output power helps to prevent discharge instabilities from occurring. However, when the partial pressure of HBr was increased to more than double that required for maximum laser output power, discharge contraction and instabilities invariably appeared.

3.2. Pulse repetition frequency

The results in Fig. 2 show an almost linear rise in the average output power with increasing p.r.f. to 20 kHz. In this particular experiment the highest average output power of 4.8 W was achieved at 23 kHz. Initially the conversion efficiency (based on stored energy) rose quickly with increased p.r.f., but between 10 and 20 kHz it was almost constant at 0.6%. Given that copper bromide lasers with active region diameters of about 2 cm are typically operated at 15 to 20 kHz [3, 7–9, 19–22], optimization of our 1.3 cm bore laser at 23 kHz comes as no surprise. However, Vetter and Nerheim [23] found that the addition of small amounts of HCl (3.5% by volume) to a double-pulse copper chloride laser halved the time delay between dissociation and excitation pulses (from 100 to 50 μs) for maximum laser pulse energy. Their studies indicated that the addition of hydrogen in the form of HCl (or H_2) reduced the copper density in the metastable lower laser levels immediately before each excitation pulse (although the rate of deactivation of the metastables did not increase), while the density of ground-state copper was raised. From their work we should therefore expect the addition of hydrogen-bearing gases to permit operation at significantly higher p.r.f.s than our 23 kHz. It is well known [7, 9] that the addition of hydrogen to a sealed-off copper bromide laser effectively doubles its output power and efficiency. However, in that case the addition of H_2 does not raise the p.r.f. that corresponds to the maximum laser output power [7, 9]. It is similarly found that the addition of hydrogen in the form of HBr does not enable laser oscillation at p.r.f.s higher than would be expected from a conventional copper bromide laser of 1 cm bore. We therefore conclude that the plasma chemistries of double-pulse copper chloride lasers [23] and multikilohertz copper bromide ([7] and this

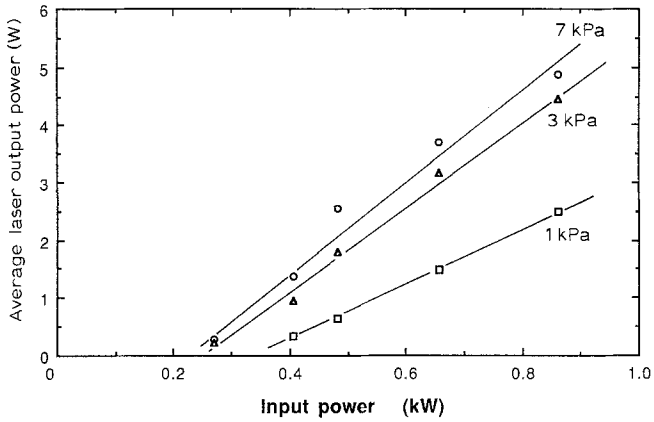

Figure 3 Average laser output power versus electrical input power at three buffer gas pressures: p.r.f. 16 kHz, HBr pressure optimized at each point.

study) lasers differ in their effects on the concentrations and relative populations of the copper neutral and ion ground states, and the laser levels. The difference may arise as a result of the fact that the interpulse concentrations of species such as copper atoms *inter alia* will depend on whether the excitation is double-pulse or continuous multikilohertz (due to cumulative excitation/production processes in the second case) [24]. Alternatively, the difference may simply be that the relative rates of reactions that involve hydrogen are different in chloride- and bromide-based lasers. The efficacy of hydrogen addition is most likely to be the result of a combination of the modified plasma chemistry of the Cu–Br–CuBr (Cu–Cl–CuCl) balance, and the alterations (due to the influence of H^-, vibrationally excited H_2 and changed Cu density) to the electron energy distribution function. Negative hydrogen ions are held by [7] to play the major role by 'shielding' the ionization of copper atoms. However, a complete explanation of these effects must await the results of a full spectroscopic and mass spectrometric study.

3.3. Input power

In Fig. 3 the dependence of average laser output power on electrical input power is shown for three diferent buffer gas pressures, when the p.r.f. was 16 kHz and where the HBr pressure was optimized for each set of conditions. It can be seen that at each pressure the output power is a linear function of input power and shows no sign of saturating. In obtaining these data the input power was conservatively maintained below about 1 kW in order to preserve the tube for subsequent experiments.

In later experiments the electrical input power was raised as high as 1.74 kW. The laser coped with this input power loading of 14.2 W cm^{-2} at the walls without any sign of a limit having been reached. For this particular experiment only, the storage and peaking capacitances were changed to 0.97 and 0.55 nF, respectively. The p.r.f. was set to 16 kHz, the Ne pressure was 7 kPa, and the HBr pressures lay in the range 90 to 200 kPa. The Saffil insulation was removed. With the input power set to 1.43 kW, the average output power was found to peak at 7.8 W (efficiency 0.54%). When the input power was reduced to 780 W the output power was still 6.1 W and the efficiency reached its maximum value at 0.8%. At maximum average output power the specific output pulse energy was 12 μJ cm^{-3}, and the

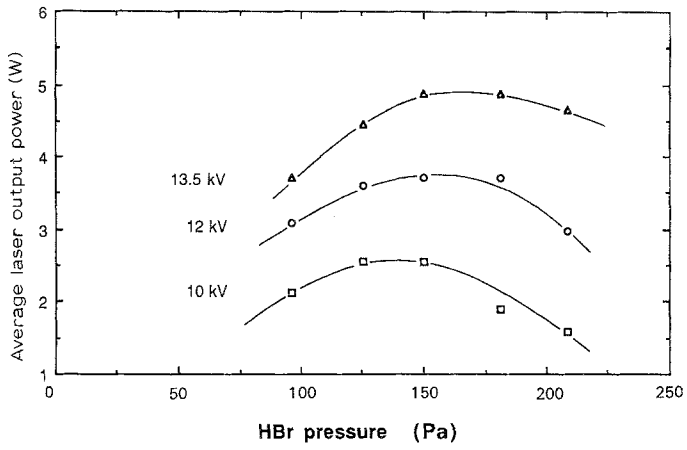

Figure 4 The dependence of average laser output power on the HBr partial pressure for three different charging voltages (input powers): p.r.f. 16 kHz, Ne pressure 7 kPa.

specific output power was 195 mW cm^{-3}. We thus see that the use of flowing Ne–HBr to provide the copper bromide by reaction *in situ* resulted in an improvement by almost a factor of 2 over the highest previously reported specific energies and powers for maximum output power in multikilohertz halide lasers of 7 μJ cm^{-3} [4] and 121 mW cm^{-3} [11].

3.4. HBr pressure

With increased charging voltage (larger tube voltage, current and input power) the optimum partial pressure of HBr (and hence CuBr concentration) also rose (Fig. 4). The optimum pressure of HBr lay in the range 100 to 200 Pa. Increased electron energies associated with higher tube voltages would be expected to enable greater HBr concentrations to be tolerated (as observed) before the energies were reduced below those optimum for excitation of the upper laser levels. The higher copper concentrations required at elevated charging voltages (greater input power loadings) are also achieved by raising the HBr pressure. Increasing the partial pressure of HBr above optimum resulted in reduced output powers and finally discharge instabilities and the cessation of laser oscillation. As well as the halogen, addition of HBr to the discharge provides hydrogen, thus ensuring efficient and powerful laser operation. However, the behaviour in Fig. 4 is in contrast to that which occurs when hydrogen is added to copper bromide lasers, since there the optimum H_2 pressure for laser output power is independent of the input power, charging voltage, Ne pressure, etc. [25]. Presumably this contrasting behaviour can be attributed to the fact that further addition of HBr acts directly to increase the copper concentration by producing more CuBr, whereas further addition of hydrogen does not.

Figure 5 shows the dependence of the average laser output power on the HBr partial pressure for buffer gas pressures of 1, 3, 5 and 7 kPa. The higher Ne pressures required higher partial pressures of HBr for maximum laser output. Conventional copper halide lasers also require higher concentrations of the halide as the buffer gas pressure is raised [26]. This behaviour is consistent with third-body assisted recombination of Cu and Br to yield increased densities of CuBr as the buffer gas pressure rises, and consequently more halide should be added to maintain the atomic copper concentration. However, this is in

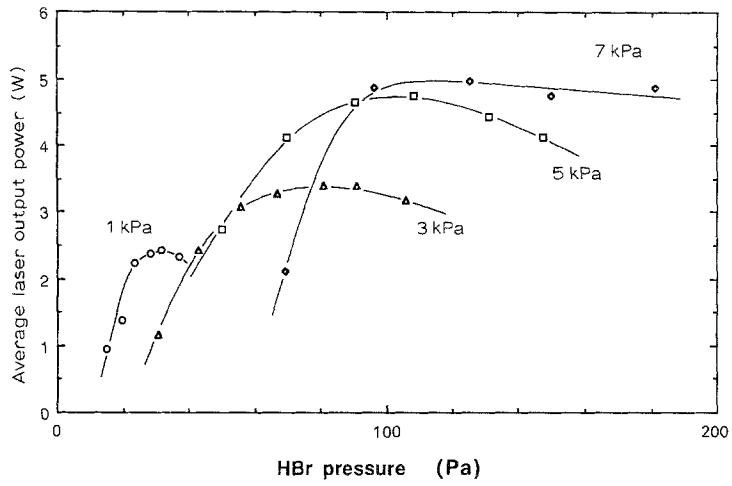

Figure 5 The dependence of average laser output power on HBr partial pressure at four different buffer gas pressures: p.r.f. 16 kHz, voltage 12.5 kV.

contrast to experiments [27] which indicate that an increase in buffer gas pressure has little effect on the density of ground-state copper in continuously pulsed copper bromide lasers. The rate of relaxation between excitation pulses of metastable copper atoms (by collisions with electrons) increases as the Ne pressure is raised [28] (presumably due to more rapid thermalization of electrons in the afterglow at higher Ne pressures). The increase in laser output power that we observed as the Ne pressure rose is thus attributable, at least in part, to reduced prepulse copper metastable densities. We may speculate further that, since many of the metastables arise from the halide dissociation process [29], a reduction in metastable density due to increasing Ne pressure will permit higher concentrations of copper halide to be tolerated. When the Ne pressure is raised, higher densities of copper halide are achieved by simultaneously increasing the HBr pressure. This leads to higher prepulse ground-state densities of copper and to larger output pulse energies, as observed in Fig. 5.

3.5. General observations

The use of a flowing Ne–HBr buffer gas permits fast start up of the laser, and small time constants in the processes that allow control of the laser output power. To illustrate the first point we took the laser, which had not been operated for 24 h, with the Ne and HBr pressures preset to 3.2 and 0.07 kPa, respectively, and turned the power supply on with the input power to the laser set at 800 W. The resulting behaviour is shown in Fig. 6. Laser oscillation first appeared 160 s after first switching on, and reached a steady state maximum output power 110 s after the start of lasing. When the thermal mass of the laser tube was reduced, and its insulation increased somewhat by the substitution of the alumina confinement tube with one of fused silica, for the same input conditions the time to lasing was reduced to only 50 s, and the additional time to maximum laser output power was just 80 s. This startup time should be compared with the 5 to 10 min of conventional copper bromide lasers and the 30 to 90 min of high temperature copper vapour lasers. Even with preheating the startup time of a small high temperature copper vapour laser is reported to be 5 to 10 min [12]. Where high powers and fast startup are the major issues, it is clear that a copper

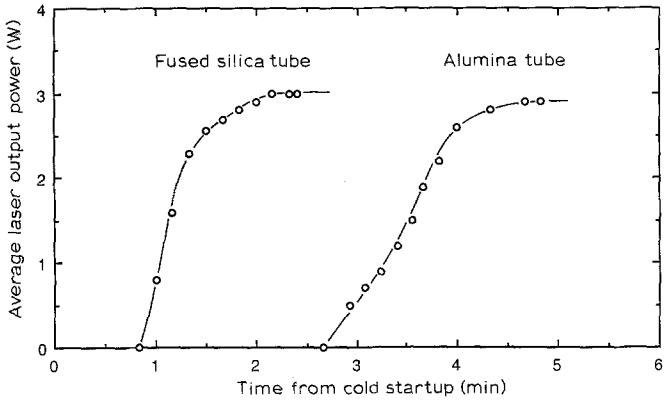

Figure 6 Laser startup characteristics: p.r.f. 16 kHz, voltage 12.5 kV, HBr pressure 70 Pa, Ne pressure 3.2 kPa.

halide laser based on flowing Ne–HBr buffer gas, with its higher specific output powers and shorter startup times, is significantly superior to high temperature copper vapour lasers.

The key to obtaining rapid control of output power from the laser is to reduce the amount of copper in the tube to no more than a few grams, and to run the laser tube wall temperature at a higher level than that corresponding to the vapour pressure of CuBr required in the discharge. These precautions ensure that no CuBr condenses out on the tube wall, so that the concentration of CuBr in the discharge is governed solely by the partial pressure of HBr present. Under these conditions, which were readily obtained in practice, the laser power could be altered with a response time of seconds. For example, turning the HBr inlet line off led to cessation of laser oscillation in typically 30 to 40 s. It should be noted that the major factor that limits the lifetime of sealed-off copper bromide lasers is not the loss of CuBr donor molecules, but the slow increase in free bromine concentration that occurs in those devices [20]. This problem with the chemistry of the Cu–Br–CuBr balance in our copper bromide laser does not occur, due to the ability to control the Br concentration in the discharge by means of the HBr inlet pressure.

With regard to laser tube lifetime, the following should be noted. The laser tube was operated continuously over a number of periods of up to 5 h each. In operation the laser discharge was remarkably stable (variations in peak discharge current and voltage were less than 2% over 60 min). However, the laser output did reduce slowly over the first hour of operation. This behaviour was associated with the growth into the discharge active region of vertical copper dendrites (up to 4 mm high). Beyond the first hour the collapse of the delicate dendrites would periodically (20 to 30 min) reinstate the laser output power to its initial magnitude, from the up to 50% reductions that would occur. Astadzhov *et al.* [7, 17] have observed copper growths on the inside surfaces of the diaphragms they use to stabilize the discharge in their conventional copper bromide laser. However, in our small-bore laser the problem of copper growth appears to be worse. We have also observed the growth of iron dendrites in a self-heated multikilohertz Ne–HBr iron bromide laser (λ = 452.9 nm) [30].

Dendrite growth also occurred in the Ne–HBr copper bromide laser referred to in [15], which was of larger bore (45 mm) and had its active region apertured by diaphragms to 40 mm. There the dendrites did not reach the laser extraction region and laser output power

was unaffected. The problem in the small-bore tube may be overcome by reducing the number of copper pieces in the laser tube, and constructing the tube of quartz with depressions along its length for the copper pieces to locate in. Alternatively, the copper pieces may be placed between wide-aperture diaphragms located in the active region. It is then envisaged that long lifetime and stable output powers may be obtained using small-bore as well as large-bore copper halide lasers based on the flowing Ne–HBr principle.

4. Conclusions

We have described a compact high power (7.8 W) copper bromide laser of simple design. Laser oscillation can be reached within a few tens of seconds of switching on the laser tube from cold, and maximum laser power delivered within 2 min of turnon. The device is efficient (up to 0.8%). Thermal insulation of the laser tube is not critical. Hydrogen, which is known to increase the efficiency and output power of copper bromide lasers, does not have to be added separately to the discharge. Besides being convenient, the technique of producing the copper halide *in situ* by reaction of a halide donor with copper in the laser tube permits an almost twofold increase in laser pulse energy per unit volume over previous types of high p.r.f. copper halide laser. We have demonstrated the Ne–HBr copper bromide laser to be capable of specific laser output energies and average powers of 12 μJ cm^{-3} and 195 mW cm^{-3}, respectively. In terms of output power per unit volume and startup time, Ne–HBr–Cu lasers appear to be superior to both conventional halide and high temperature copper vapour lasers.

The technique described may be applied to a whole range of lasers that use transitions in metal atoms (their application to metal vapour ion lasers will be limited to a large extent by the reduction in the numbers of high energy electrons associated with the introduction of molecules such as HBr). Recent experiments in which the technique of generating metal halides *in situ* to permit multikilohertz laser oscillation on cyclic transitions in lead [31], bismuth [32] and iron [30] will soon be reported.

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