Construction of a practical sealed-off He–I⁺ laser device

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Abstract By improving the system for control of iodine vapour pressure with molecular sieves in a positive-column He–I$_2$ discharge, it has been possible to construct a stable sealed-off He–I⁺ laser device for the visible region. It has a total laser power of 20–30 mW for five visible lines, and a lifetime longer than 1000 h. Details of the construction and operation of the practical He–I⁺ laser are reported. The characteristics of the laser power are also described.

1 Introduction

Pulsed laser oscillation in singly ionized iodine was observed first in 1964 by Fowles and Jensen. CW laser oscillation was realized for only one transition (612·7 nm) in a He–CdI$_2$ gas mixture in 1972 by Collins *et al*, and then for ten visible and near-infrared transitions in a hollow-cathode He–I$_2$ discharge by using a flowing-gas system (Piper *et al* 1972).

Until then, continuous laser oscillation in the positive column He–I$_2$ discharge had not been realized, perhaps because of high iodine vapour pressure, 100–200 Pa, at room temperature. In the past, we had no way of overcoming this problem except by the use of an inconvenient cooling system. Previously we developed a method to control it by using molecular sieves and obtained CW laser oscillation of five visible lines (Hattori *et al* 1974a) in singly ionized iodine which were excited by charge transfer collision (Shay *et al* 1975).

The hollow-cathode laser using the flowing-gas method developed by Piper and Webb (1973) may be promising as a high-power laser because they have not observed any saturation of laser power with increasing discharge current (Piper 1974). In constructing a practical sealed-off laser, probably the positive-column discharge is preferable to the hollow-cathode discharge because we can use the convenient cataphoresis effect to control metal vapour pressure and utilize the technique and simple tube used in He–Ne and He–Cd⁺ laser systems.

From these results and speculation, we have made the first sealed-off He–I⁺ laser using positive-column discharge (Hattori *et al* 1974b). The total laser power of five visible lines

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was roughly 40 mW at maximum and the lifetime of the tube was about 200 h. We could also obtain laser oscillation for four near-infrared lines by replacing the laser mirrors (Kano *et al* 1975). In this tube, however, since iodine molecules accumulated in the cathode region could not be eliminated very efficiently, the laser power tended to decrease slowly with time during operation of a few hours and appreciable sputtering of a hot cathode by the iodine was observed.

In this work, we obtained considerable improvements in the sealed-off He–I⁺ laser and constructed a practical laser device of stable laser power and long life. We report here the details of the construction and operation of this He–I⁺ laser and discuss the power, stability, tube lifetime and characteristics of the laser beam, e.g. gain, noise and mode.

2 Construction of a laser device

2.1 *Method of control of iodine vapour pressure*

In the positive-column He–I⁺ laser, laser oscillation was obtained at an iodine vapour pressure of about 1 Pa (Kano *et al* 1973, Hattori *et al* 1974a) and a temperature of -20 to $0\,°C$ with metallic iodine. In our He–I⁺ laser system, molecular sieves (type 5A, Union Carbide Co.) have been used for obtaining this pressure at a convenient operating temperature of an iodine reservoir. They have three desirable characteristics in the He–I⁺ laser: (i) they adsorb iodine molecules very well, but not helium atoms at room temperature; (ii) they can adsorb a large amount of iodine in a small volume because of their large adsorption surface; (iii) the optimum vapour pressure in the laser is obtained by warming the molecular sieves with the control system similar to that used in the He–Cd⁺ laser.

Before the molecular sieves were packed in the side arm of the laser tube, the impurity gases adsorbed in them were evacuated to pressures of 10^{-1}–10^{-2} Pa by heating them at $450\,°C$. Afterwards, the molecular sieves were used at temperatures below $200\,°C$; the impurity gas pressure was below 10^{-4} Pa which did not affect laser action. Next, the iodine was adsorbed by the molecular sieves and laser oscillation was produced by warming the molecular sieves.

Because the vapour pressure of iodine is high at room temperature, we need to eliminate the iodine atoms at the cathode region. Otherwise, these atoms, pumped by the cataphoresis effect in the positive column, accumulate at the cathode and the iodine density in the positive column becomes too high for laser oscillation. The baked molecular sieves were placed in front of the cathode to eliminate the iodine molecules and retain the axial uniformity of iodine density inside the positive-column He–I₂ discharge.
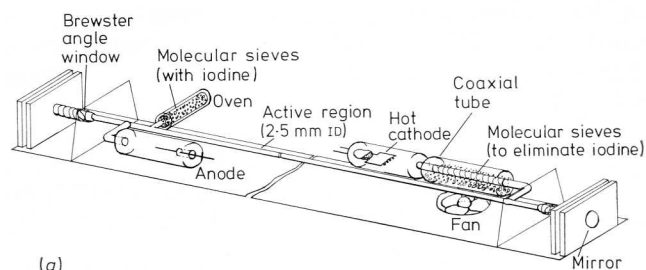
2.2 *Laser device*

Our device is shown in figure 1. The essential parts are the iodine reservoir and the coaxial part of the tube where the molecular sieves adsorb iodine molecules pumped to the cathode. The other parts are almost the same as in commercially produced He–Ne and He–Cd⁺ lasers.

The active region of the laser tube was 2·5 mm in diameter and 100 cm in length. A laser cavity was constructed with two concave mirrors which had high reflectivities of 100% and $97·5\%$ respectively at 450–650 nm and were placed at a separation of 140 cm. The cathode was made with a tungsten filament for obtaining a relatively high current of about 280 mA.

The iodine reservoir, comprising the molecular sieves which had adsorbed iodine molecules and the side arm as a container for them at the anode side, was heated with a temperature-controlled heating system.

The improved configuration of the container of the baked molecular sieves in the cathode side is illustrated in figure 2.
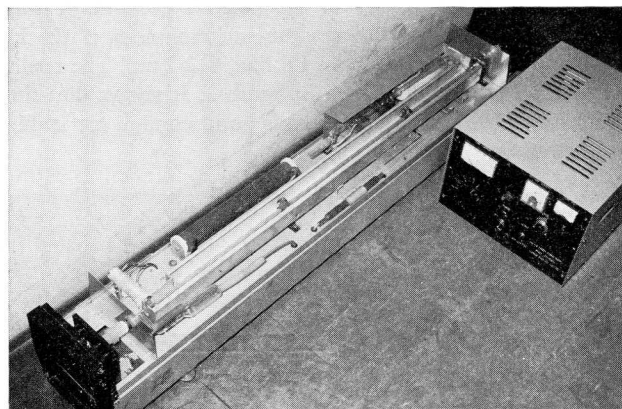
(b)

Figure 1 (*a*) Diagram of practical sealed-off He–I⁺ laser; (*b*) photographic view of the actual He–I⁺ laser device (made by the Kimmon Electric Co. Ltd)

In the last experimental tube, shown in figure 2(*a*), the side arm that contained molecular sieves was simply put on the opposite side of the cathode, so that the efficient surface through which iodine molecules could be adsorbed was comparatively small. Moreover, it was possible for the iodine molecules to be pumped to the cathode by the cataphoresis effect. In the present tube, we put the coaxial part between the cathode and active discharge as shown in figure 2(*b*). In this configuration the efficient surface for adsorption of iodine molecules was enlarged and iodine molecules were eliminated before their arrival at the cathode. A small fan was used to dissipate heat produced by the discharge. This new configuration improved
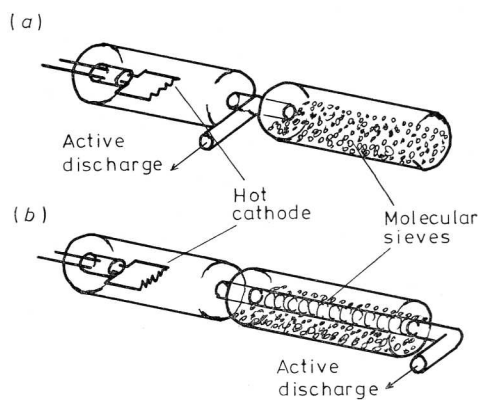

Figure 2 Molecular sieves container in the cathode region where the iodine molecules pumped by the cataphoresis effect in positive-column discharge are eliminated. (*a*) is the configuration of the last reported laser tube; (*b*) is the coaxial configuration used in the present laser

the ability to eliminate iodine molecules. By solving the axial and radial diffusion equations for iodine atoms and ions, we found that the iodine particles could be eliminated almost completely (99%) after passing along this coaxial part, 10 cm in length.

The improvement helped to reduce markedly the sputtering of the cathode which might shorten the lifetime of the tungsten heater, contaminate the Brewster window gradually and possibly reduce helium pressure by adsorbing helium atoms during the process (Sosnowski and Klein 1971).

The improvement also had an effect on the axial uniformity of the iodine atom density in the positive column. It was monitored by observing the spontaneous emissions of the I I atomic line at 511·9 nm, and an I II line, 612·7 nm. The result for the 612·7 nm line is shown in figure 3. It shows that the uniformity of the iodine density was good enough for stable laser operation.
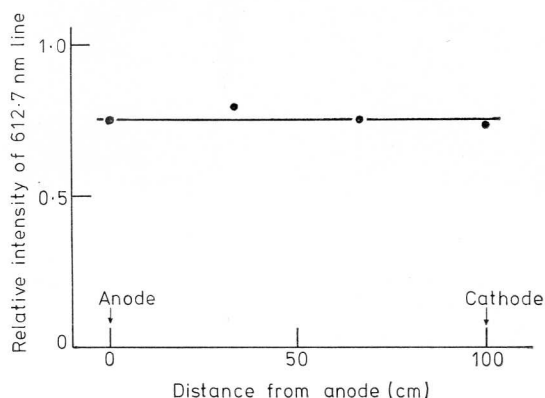

Figure 3 Relative intensity of the I II 612·7 nm spontaneous emission line as a function of distance from the anode. It shows the very good axial uniformity of the iodine atom density in the He–I_2 positive-column discharge

3 Operation

In the He–I$^+$ laser device, laser oscillation could be obtained at the I II 540·7, 567·8, 576·1, 612·7 and 658·5 nm transitions $(6p'^3D_{1,2}, {}^3F_2-6s'^3D_{1,2}^0)$. However, when we replaced the mirrors in the same system, this immediately produced laser oscillations at the 703·3, 761·8, 817·0 and 880·4 nm transitions $(6p'^3D_2, {}^3F_2-5d'^3D_{2,3}^0, {}^3F_3^0)$ in the near-infrared region, which we reported earlier (Kano *et al* 1975).

The output characteristics of visible lines were discussed in our other report (Hattori *et al* 1974b). From those data we have chosen the operating conditions in the sealed-off He–I$^+$ laser: a helium pressure of 800 Pa, an operation current of 280 mA and an oven temperature of about 130°C.

This helium pressure was slightly higher than that for obtaining the maximum laser power, but we filled the tube at this pressure because we were afraid of a clean-up of helium gas, which was considerable in the He–Cd$^+$ laser (Sosnowski and Klein 1971). The operation current was smaller than that of the last tube because the tube diameter was smaller than the previous one (Hattori *et al* 1974b). It was thought that the smaller current might help to prolong the lifetime of the heated tungsten cathode.

The iodine vapour pressure at a certain temperature depends on the relative amounts of the iodine and molecular sieves. For example, we used 5 g of iodine with 50 g of molecular sieves and had an operating temperature of about 130°C. When the quantity of the iodine was increased, the operating temperature decreased.

It is not easy to estimate the iodine vapour pressure at the optimum conditions directly from the oven temperature in the laser tube, so we adopted another method. In positive-column He–metal discharge, the electron temperature and tube voltage in the positive-column region drop as the metal vapour pressure increases (Goto *et al* 1971, 1972). We obtained the relation of voltage drop to metal vapour pressure in the positive-column He–I_2 discharge (Hattori *et al* 1974a). By measuring the voltage drop carefully once more in the He–I_2 discharge and making the relation more accurate, we estimated the iodine vapour pressure to be 2·6 Pa under the optimum conditions with a tube voltage of 3·4 kV.

In this device the total power of the five visible lines was 20–30 mW, slightly lower than that in the last laser system, 40 mW (Hattori *et al* 1974b). Two reasons can be offered to explain the difference; one is that the active length was somewhat shorter; the other is that the transmission loss of the mirror was fixed at 2·5%, which was probably not the optimum matching loss. When we used the laser cavity with two mirrors having a reflectivity of 100% and a coupling quartz plate by which we could change the cavity loss, the power was about 40 mW at maximum. Thus it is considered that the available maximum laser power in the present laser is of the order of 40–50 mW even if other mirrors are used.

During the experiment we observed fluorescence in the region between the Brewster window and the edge of the active plasma in the cathode side, where there was no discharge so that iodine molecules could exist. This fluorescence might result from laser beam excitation of iodine molecules, because molecular iodine has an absorption band structure which covers the wavelength region of the laser lines (Sulzer and Wieland 1952). The laser power may be reduced by this absorption. One method for removing the iodine molecules from this region is to make an auxiliary discharge between the cathode and window, in the direction from the window to the cathode, with a small auxiliary anode.

We monitored the total laser power at every hundred hours throughout the experiment. No detectable reduction in laser power was observed during 700 hours' operation. The laser windows and the wall surface of the capillary of the laser tube were still clean and the envelope of the hot cathode was not coloured by sputtering. After 1000 hours' operation, the laser power was reduced only by a few per cent compared with the initial power level. At that time we could not see any contamination on the laser windows, but we could see spots in the capillary of the tube and a coloured film on the inside surface of the cathode envelope.

4 Characteristics of the laser output power

Studies were made of laser output power, particularly drift, ripple, noise, mode and gain which become important factors in some applications.

In the He–metal lasers, such as the He–Cd$^+$ laser, it takes a long time to produce stable laser oscillation without a drift of power because of the heating of the metal. In the He–I$^+$ laser system this time was shorter than in the He–Cd$^+$ laser.

By using a spectral analyser and oscilloscope, we observed the fluctuation of the laser power in three frequency regions: very low-frequency fluctuations, caused by the drift of laser power during a long operation; those of frequencies of 60 and 120 Hz, caused by the ripple of the power supply; and relatively high-frequency noise at 1–100 kHz. The drift of the laser power from the initial power level was not noticeable compared with the other power fluctuations. The power supply used for the excitation of the laser tube had rather large ripples of 60 and 120 Hz due to inadequate filtering, so ripple was observed in the laser power.

High-frequency noise from 1 to 100 kHz decreased approximately with $1/f$, where f is the frequency, and had a hump at a frequency of about 100 kHz. The averaged ratio of this high-frequency noise to the DC level of the laser power was 10–15%, which was smaller than the power of the Cd II 441·6 nm laser in the positive-column He–Cd⁺ laser obtained with a similar system.

Iodine has only one common isotope, so the gain profile may be simple, as opposed to the complicated one in the He–Cd⁺ laser. The actual longitudinal mode structure of the I II 612·7 nm line measured with a Fabry–Perot scanning interferometer is shown in figure 4. It consists of five relatively large modes and its envelope forms an approximate Doppler-broadened profile. On the other hand, the transverse mode structure of the 612·7 nm line consisted of a simple TEM₀₀ mode
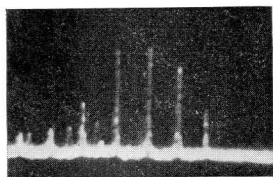

|—⊣
100 MHz

Figure 4 Mode spectrum of laser oscillation at the I II 612·7 nm line. Its envelope is decided approximately by Doppler broadening

and was very stable because of the small tube bore. The other four lines had the same mode structures as the 612·7 nm line.

The gains of the laser lines were about 4% m⁻¹ for the 576·1 and 612·7 nm lines and lower for the other lines in the 2·5 mm bore tube.

The drift of the laser power was small enough for normal applications. Although the ripple was somewhat large, it can be reduced easily by using a better power supply. The high-frequency noise was still too large for some applications. However, it was found that the noise was decided mainly by the $1/f$ distribution. This $1/f$ noise is considered to come from the discharge, particularly from the electrode regions. One method of reducing this noise spectrum is to put the grid in front of the cathode and anode (Takayama 1962). With this improvement and others, we may make the He–I⁺ laser device low-noise in future. Although the gains are somewhat lower than 4–5% m⁻¹ for the He–Cd⁺ laser (Silfvast 1968) and the He–Se⁺ laser (Silfvast and Klein 1970), it is supposed that they are sufficient to produce a practical laser power.

5 Conclusions

The use of molecular sieves enabled us to control the iodine vapour pressure in the positive-column He–I⁺ laser with the same heating system as that used for the He–Cd⁺ laser. We then constructed a practical sealed-off He–I⁺ laser device having five stable lines in the visible region.

In this device, because the efficiency of elimination of iodine and the sputtering of the cathode were considerably improved, the laser tube was very clean and the decrease of helium pressure and laser power was not considerable even after 1000 hours' operation. Therefore, although the discharge current of this laser is higher than that of the He–Cd⁺ laser, it is expected that the life of the iodine laser is fairly long.

The power of the He–I⁺ laser was 20–30 mW, low compared with that of the positive-column He–Cd⁺ laser. However, the lines of the former occur in the green to near-infrared region while those of the latter are in the violet to near-ultraviolet region. Therefore, these two lasers are complementary rather than competitive and both can be useful as practical lasers.

References

Collins G J, Kuno H, Hattori S, Tokutome K, Ishikawa M and Kamiide N 1972 *IEEE J. Quantum Electron.* **QE-8.** 679–80

Fowles G R and Jensen R C 1964 *Proc. IEE* **52** 851–2

Fowles G R and Jensen R C 1964 *Appl. Opt.* **3** 1191–2

Goto T, Kawahara A, Collins G J and Hattori S 1971 *J. Appl. Phys.* **42** 3816–8

Goto T, Kano H and Hattori S 1972 *J. Appl. Phys.* **43** 5064–8

Hattori S, Kano H, Tokutome K, Collins G J and Goto T 1974a *IEEE J. Quantum Electron.* **QE-10** 530–1

Hattori S, Kano H and Goto T 1974b *IEEE J. Quantum Electron.* **QE-10** 739–40

Kano H, Goto T and Hattori S 1973 *IEEE J. Quantum Electron.* **QE-9** 776–8

Kano H, Goto T and Hattori S 1975 *J. Phys. Soc. Japan* **38** 586

Piper J A, Collins G J and Webb C E 1972 *Appl. Phys. Lett.* **21** 203–5

Piper J A and Webb C E 1973 *J. Phys. D: Appl. Phys.* **6** 400–7

Piper J A 1974 *J. Phys. D: Appl. Phys.* **7** 323–8

Schuebel W K 1970 *Appl. Phys. Lett.* **16** 470–2

Shay T, Kano H and Collins G J 1975 *Appl. Phys. Lett.* **26** 531–4

Silfvast W T 1968 *Appl. Phys. Lett.* **13** 169–71

Silfvast W T and Klein M B 1970 *Appl. Phys. Lett.* **17** 400–3

Sosnowski T P and Klein M B 1971 *IEEE J. Quantum Electron* **QE-7** 425–6

Sulzer P and Wieland K 1952 *Helv. Phys. Acta* **25** 653–76

Takayama K 1962 *Rev. Elect. Commun. Lab.* **10** 100