Design of a hollow-cathode discharge CW He-Cd⁺ multicolour laser module

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1. Introduction

Today, in the fourth decade of the vivid development of laser technology there is still a permanent demand for simple, reliable and cheap laser systems simultaneously generating the three primary spectral lines: blue, green and red, a mixture of which can result in a wide band of colours. This demand is mainly due to the fast introduction of laser to the information processing, including full colour printing, film to video conversion and vice versa, film recording and reproduction, image simulation, displays, holographic recording and storage, and optical data storage. Among other possible applications there are surface inspection (e.g. medical endoscopy, laser colour microscopy), inspection of photosensitive materials, and multicolour measurements.

Since its first introduction [1 - 5] the hollow-cathode discharge (HCD) He-Cd⁺ laser has been one of the most promising candidates for such a multicolour laser system. The HCD He-Cd⁺ laser oscillation wavelengths in red (636.0 and 635.5 nm), green (537.8 nm and 533.7 nm), and blue (441.6 nm) are close to those of the ideal three primary spectral lines (610 nm, 640 nm, 450 nm) [5], thus offering a chance for a very wide range of colour reproduction. This has been proved when Fujii et al. [7] obtained simultaneous, well colour-balanced oscillations in red, green and blue with their flute type HCD He-Cd⁺ laser. The beam emitted by this laser appeared white, therefore following the inventors a HCD HeCd⁺ laser emitting such a beam is commonly called a HCD He-Cd⁺ white-light laser. High ability of the HCD He-Cd⁺ white-light laser to reproduce full colour pictures has been practically shown by Takashima et al. [8]. Moreover, demonstration of multicolour lasing of the HCD He-Cd⁺ laser at an output power close to 200 mW and noise-to-signal ratio lower than 1% (Fuke et al. [9]) improves the commercial attractiveness of the HCD He-Cd⁺ white-light lasers. Unfortunately, severe technological problems associated with control of pressure and distribution of the metal vapour in the discharge region, discharge uniformity and stability, the gas component separation due to cataphoresis, erosion of the cathode surface due to discharge sputtering, build-up of gaseous impurities, loss of the He buffer gas, etc., which shorten the lifetime of the HCD He-Cd⁺ white-light lasers to hundreds of hours, have so far made this laser impractical for commercial applications.

There have been a great deal research done on various features of the HCD He-Cd⁺ laser, using for the experiment purposes pulsed or half-rectified discharge currents for the laser excitation. However, development of a practical CW HCD He-Cd⁺ laser, excitation of which is inevitably associated with direct current (DC) excitation, has been attempted by several researchers only. The DC excitation of the HCD He-Cd⁺ laser causes new technological problems, mainly associated with heat dissipation, temperature distribution in the discharge tube and electrical arcing, which have not been met under pulsed or half-rectified discharge current excitation. Since this paper mainly concerns the problems associated with implementation of the HCD He-Cd⁺ white laser as a commercial device, further an we will only refer to those previous publications, which dealt with the problems arising from the DC excitation.

A survey of the works on the DC-excited HCD He-Cd⁺ whitelight lasers shows that there have been two directions in the development of a practical HCD He-Cd⁺ white-light laser system. The first direction has been aimed at developing the laser which consists of one or more short-cylinder hollow cathode modules having physically robust structure. In such a design regulation of the operating parameters, including distribution of the cadmium vapour and discharge current along the hollow cathode is relatively simple. Mainly due to this simplicity, 1000-hours operating lifetimes have been achieved in some of the short-cylinder HCD He-Cd⁺ white-light lasers. This development direction is represented by the laser designs processed by Fukuda and Miyazaki [10], Hernquist [11], Kawase [12], Wang [13], Mizeraczyk et al. [14,15], Bergmann et al. [16], Sasaki et al. [17], and Tsuda and Piper [18]. The second direction represented by the designs of Fujii et al. [19,20], and Fuke et al. [9,21,22], concerns the development of the long-cylinder hollow-cathode He-Cd⁺ whitelight laser. Such laser operation problems as discharge stability and uniform distributions of the cadmium vapour and discharge current in the hollow cathode, inherently associated with using the long-cylinder hollow cathode are more pronounced in this case. To overcome these problems, it is possible at all, rather sophisticated electronic control of temperature along the laser tube in necessary, as was shown by Fuke et al. [9,21,22].

Because of the technical problems a HCD He-Cd⁺ white-light device seems to be unavailable at the laser market at present. Although indeed such a device have structure resembling the design of Fuke et al. [9,21,22] appeared as a product of Nihon Densa Kogyo Co., Ltd, Japan at the laser market some years ago, it has been shortly withdrawn, at least from Europe. The models of the HCD He-Cd⁺ white-light laser device based on the designs of Kawase [12], Wang [13], and Fuke et al. [9,21,22] were presented at the laser exhibitions [23-25].

In this paper we present results of our effort to develop a simple HCD He-Cd⁺ multicolour light device exhibiting longlife stable operation at milliwatt output power levels. We assumed that the laser device should meet the following requirements:

a) The laser head should consist of a simple short cylinder hollow-cathode module. Such a design assures good stability of the laser operation and long operating lifetime (1000 h). Relatively low output powers, in particular in the green and red, inherently associated with the short-module laser can be increased in a laser configuration consisting of more modules.

b) The discharge current and cadmium vapour density in the hollow cathode should be independently controlled.

c) The temperatures of the hollow cathode and Cd reservoir must be accurately controlled. To achieve uniform cadmium vapour distribution along the hollow cathode the temperature gradient along the cathode should be minimized.

d) For minimizing the temperature gradient along the hollow cathode and optimizing excitation efficiency the discharge current must be properly distributed along the hollow cathode.
2. Design and conditioning of the HCD He-Cd⁺ laser tube

For more practical realization of a simple HCD He-Cd⁺ multicolour laser we have chosen a laser module concept of Mizeraczyk et al. [14, 15] as that which seems to meet most of the operating conditions listed above. Following this concept we designed a HCD He-Cd⁺ laser module, geometry of which is shown in Fig. 1. The laser cab consists of one or more modules, depending on the laser output power desired. The laser module presented consisted of two anodes, located on opposite sides of the hollow cathode and separated from it by fused silica capillary tubes (3 mm inner diameter, 5 cm long). The anodes were made of tungsten rod having a diameter of 1 mm. The positive columns created in the fused silica capillary tubes, as parts of the glow discharges established between the anodes and the cathode, served to confine the cadmium vapour within the cathode region by cathophoretic action. The laser tube part including the fused silica capillary tube and the neighbouring region is called cathophoretic confinement section, after Herquist [11, 26]. Efficiency of the cadmium vapour confinement within cathode region by the cathophoretic confinement section seems to be very effective, if not perfect, since we were not able to see any traces of cadmium having diffused out of the cathode region after hundreds hours of the laser operation, similarly as Herquist [27] and Mizeraczyk et al. [28]. Using alumina oxide ceramic capillary tubes with machinable ceramic inserts as a tightening between them and the outer glass tube, instead of fused silica capillary tubes in the confinement sections, failed because they deteriorated the cadmium confinement, presumably due to a relatively high thermal conductivity of the machinable ceramic used (Corning “Macor”). A relatively long glass sidearm with a narrow inner diameter of 5 mm, the end side of which served as a temporary reservoir of distilled Cd pellets was connected to one of the cadmium confinement sections.

The He-Cd positive columns built up in the cathophoretic confinement sections on the axis of the HCD He-Cd⁺ laser may contribute to absorption of the generated laser lines and thus decrease the output power of the laser, in particular if multi-module laser configuration is considered. However, in a separate experiment [29] we found out that the absorption of the 441.6 nm He-Cd⁺ laser line by the He-Cd positive column used for cadmium confinement is relatively low (about 0.1% per a few cm long He-Cd positive column). Estimates show that such a low absorption should not decrease the 441.6 nm output power of HCD He-Cd⁺ laser more than a few percents. Possible absorption of the other lines of the HCD He-Cd⁺ laser, i.e. the red and green are not known. The hollow-cathode section of the laser tube consisted of a massive Kovar tubing with an outer diameter of 25 mm.

The cathode was bored to a bore of diameter of 4 mm and length of 2 x 50 mm with a wider cylindrical section (length 10 mm, diameter 10 mm) in the cathode middle. The wider cylindrical section of the cathode plays important role for the discharge operation. It separates both discharges established in the narrow-bore parts of the cathode and makes them stable and symmetrically distributed along both narrow cathode bores. Because of the feasibility of making the long bores the cathode consisted of two identical parts which after arg-welding (also laser welding was positively tested) forms the hollow cathode, as shown in Fig. 1. After the welding and putting ceramic inserts, preventing the discharge from running also to the cathode parts other than the bore (which also decrease the cathode sputtering), the hollow-cathode segment was cleaned by simultaneous pumping and baking up to about 1200 K during several days. Then the glass parts of the laser tube, i.e. cadmium confinement sections, anode and Brewster window regions were sealed with Kovarborosilicate glass tubular joints to the cathode segment. The Brewster fused silica windows were sealed by soldering them to the fused silica extension stubs. Thus the whole laser tube except the long glass outlet serving as temporary Cd reservoir, could be baked under vacuum up to about 750 K.

The procedure of the laser tube conditioning was as follows. First the tube with distilled Cd pellets in the endside of the long glass sidearm of the temporary Cd reservoir was connected to a conditioning system with feasibility of high vacuum pumping, gas handling and tube baking. The whole tube, except the temporary Cd reservoir, was simultaneously pumped and baked up to 750 K for 24 hours. Then the tube was conditioned with the discharge in pure hydrogen (10 mbar, 200 mA in total through both anodes) under flow gas condition for several hours. This should have caused desorption of oxygen from the cathode surface. Next, once more the tube was simultaneously pumped and baked up to 750 K for 24 hours. After cooling the tube to room temperature, the Cd pellets were distilled from the temporary Cd reservoir into the cadmium confinement section, and tube was flame sealed, keeping vacuum in it, directly at the temporary Cd reservoir side-arm connection to the cadmium confinement section.

Now, the vacuumed tube was separated from the conditioning system by sealing it at one of the vacuum-tight gas inlet sidearms. After mounting a heavy wall aluminium cylinder (with electrical heaters in it) as a hollow-cathode envelope, and two ovens outside the cathophoretic confinement sections (see Fig. 1), the laser tube was connected through one of the remained gas inlet sidearms to a high-vacuum (10⁻⁶ mbar) and gas handling system with facilities for delivering He and He from the flasks (helium purity 0.999986) directly or through permeation glass filter [30]. Then, after breaking through the vacuum, the gas inlet tube underwent the final conditioning procedure with the discharge and helium exchange for several hours under external heating of the hollow-cathode region, using the electrical heaters in the cylindrical Al-block. During this process the cathophoretic confinement section containing redistilled cadmium was kept at a temperature below 400 K at which cadmium did not practically vaporize. Next, by running the discharge (always from the two anodes) and adequate heating the cathophoretic confinement sections with no external heating of the hollow cathode, the cadmium from one of the confinement sections was introduced into the hollow cathode by cathophoresis and diffusion so that it formed a thin layer on the inner walls of the hollow cathode. This accomplished the conditioning procedure.

![Fig. 1. Scheme of the HCD He-Cd⁺ laser module and expected distribution of Cd vapour in the module.](image-url)
The requirements of accurate temperature control of the hollow cathode and Cd reservoir, and minimizing temperature gradient along the hollow cathode are critical for efficient operation of the HCD He-Cd⁺ white light laser. We found out that even the massive kovar tubing of a diameter of 25 mm, used as a hollow cathode in this work could not assure a uniform temperature distribution along the hollow cathode (Fig. 2). This is due to the strong inhomogeneous distribution of the discharge current along the cathode caused by the outside positioning of the anodes regarding the hollow cathode (the so-called longitudinal hollow cathode discharge [31]). However, since the cathode is directly accessible from the outside in this design, the above-mentioned heavy wall Al cylinder having high thermal conductivity was incorporated in intimate thermal contact with the hollow cathode. This Al cylinder served, first, for minimizing the temperature difference along the hollow cathode, and second, for controlling the hollow cathode temperature with the electrical heaters placed in it. The outside diameter of the Al cylinder was fixed at 60 mm to get the heat dissipation enough high so that without using the heaters the hollow cathode temperature resulted from the heating by the discharge was always lower then about 450 K (Fig. 3). At this temperature the Cd vapour pressure is well below the optimum needed for the laser operation. Only using the heaters externally controlled with a thermostat (on- and off-duty) provided the hollow-cathode temperature optimum for the laser.

The concept of regulation of the cadmium vapour density in the hollow-cathode was as follows. Having cadmium distributed as a thin layer inside the hollow cathode, we started the discharge and the simultaneous heating of the hollow-cathode and cadmium confinement sections with the electric heaters and both side-end ovens, respectively. The heating was so performed that after reaching 450 K temperatures of both confinement were always maintained about 20 K above the hollow-cathode temperature. At given temperatures of the hollow cathode (Tmc) and cataphoretic sections (Tc) the density of cadmium vapour in the hollow cathode corresponds to the saturated pressure of the Cd vapour produced above the Cd thin layer deposits having the temperature Tmc, whereas the Cd vapour in the cataphoretic confinement sections is in unsaturated vapour diffused into them from the hollow-cathode region. Since Cd vapour in the confinement sections cannot diffuse towards the anodes due to cataphoresis, the unsaturated Cd vapour density in the confinement sections is defined by the saturated pressure of the Cd vapour in the hollow-cathode region, and temperature Tc. As a result such Cd vapour density distribution along the laser tube as illustrated in Fig. 1 is expected. Raising both temperatures Tmc and Tc, the Cd vapour density corresponding to the maximum output laser power can be achieved. During operation the temperatures of the hollow cathode and side-end ovens were stabilized within 10.5 K by a thermostat with thermocouple sensors placed in the Al-block and both side-end ovens. However, due to more reliable correlation between the laser output power and the anode-cathode voltage (Figs. 4 and 5), a better stabilization of the laser output power was observed when the thermostat was controlled by the voltage drop between the anodes and the hollow cathode rather than by the thermocouple sensors.

The discharge was maintained by a nonstabilized dc power supply from which the current was delivered through two 2.5 kΩ resistors which ballasted each anode. A typical discharge current flowing to each anode was 130 mA. Due to the particular cathode design and the precautions taken against nonuniform distribution of Cd vapour along the hollow cathode both discharge currents flowing to the anodes were equal and stable within ±5 mA limit.

For the multiline operation, including white-light emission, high-reflecting (R > 99.9%) broad-band mirror pairs, separated by a distance of about 70 cm were used. Their radii of curvature were by no means optimized for maximum laser power extraction from the optically active volume of the laser. For the laser line selection and single-line operation a birefringent filter [32] inserted in the laser resonator was used. Small-signal gains on the laser transitions were measured with an intracavity computerized assembly having two counter-rotating Fresnel plates, which we use as a routine procedure for measuring internal losses of a laser resonator [33]. The maximum laser output power was extracted from the laser resonator with a Fresnel plate, set as the optimum outcoupling angle in it.

3. Laser performance

Due to the particular cathode design the discharge currents to both anodes were stable and symmetrically distributed along the narrow-cylinder parts of the hollow cathode. This resulted in stable and effective cw multicolour laser operation at seven wavelengths in blue (λ = 441.6 nm - 3 mW), green (λ = 533.7 nm - 0.3 mW, λ = 537.8 nm - 0.4 mW), red (λ = 635.5 nm and λ = 636.0 nm - total 0.2 mW) and infrared (λ = 723.8 nm and λ = 728.4 nm - total 0.1 mW). The corresponding small-signal gains were: 12, 11, 15, 4.5, and 3.7% m⁻¹. All these values were
obtained for a higher order transverse mode operation of the laser. The optimum He pressure, Cd vapour pressure and total discharge current were: 8 mbar, 0.01 mbar (corresponding to the temperature of 533 K) and 260 mA. The optimum operating voltage between the anodes and the cathode was 430 V. No influence on the laser performance was observed using He as a buffer gas, instead of pure He. Without external means of stabilization of the output power, except for the temperature, the short-term laser output power variations were lower than 1% peak-to-peak (Fig. 6). The drift of laser output power per hour was also lower than 1%. Till the closing experiment the laser has exhibited stable operation for 300 hours without discharge deterioration. The above allows us to predict that the presented HCD cw He-Cd⁺ laser module should be useful as a simple, short, long-lived, multi-colour laser source, operating at output power levels of milliwatt.

Despite almost tenfold increase of the laser output compared to that earlier reported for the similar 10 cm long laser module [14, 15], the laser output offered by our 10 cm long module can be insufficient for many practical applications. Therefore, for higher output power level demand three or four laser modules must be used. Such a multi-module laser would operate at output power levels of tens of milliwatts [14, 15].

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References


