PROGRESS IN THE DEVELOPMENT OF A THREE-COLOR CADMIUM-VAPOR LASER WITH DISCHARGE IN A HOLLOW CATHODE

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1. INTRODUCTION

The most important advantage of lasing transitions in metal ions is the feasibility of achieving cw lasing in a wide range of wavelengths – from the near IR to the UV. This is accompanied by a more complete realization of important gas-laser properties as high monochromaticity, coherence, directivity of the radiation, and a low noise level (in some excitation regimes). This makes these lasers unrivaled in many applications, such as high-speed high-density information recording on photomaterials, holography, spectroscopy, and others [8].

The cw metal-vapor ion laser most investigated and made commercially feasible is the cadmium-vapor laser with a capillary dc-discharge positive column (PC) excited in a mixture of cadmium vapor with helium (Cd II lasing wavelengths 441.6 and 325 nm). A serious obstacle to more applications than available at present for a cataphoretic cadmium-vapor laser is the high radiation noise level, which reaches from several to several dozen percent, and the distortion of the ion laser-line contours by ion drift in the PC field.

Following the pioneering work of the staff of the Rostov university towards attaining pulsed and cw lasing on ion transitions in a hollow-cathode discharge (HCD) [2, 3], numerous studies by Soviet and foreign workers have established that in negative emission (NE) of an HCD pumping ionic metals by impact of the second kind with helium (charge-exchange and Penning process) is much more effective than in a PC, making lasing possible in HCD on a considerably larger number of such transitions than in PC, and with a noise level smaller by 1-2 orders [1]. Thus, in a helium–cadmium mixture in a cw HCD lasing is possible not only on the aforementioned UV and blue lines, but also on green (533.7 and 537.8 nm), red (635.5 and 636) and a number of IR transitions.

It can be seen that the wavelengths of a laser with HCD in the visible are close to the ideal primary collers – the "peaks" of the CIE color triangle – 450, 540, and 650 nm [4], additive mixing of which yields the natural "white light." This laser is therefore frequently called "white-light laser" in the literature.

2. FEATURES OF EXCITATION OF IONIC TRANSITIONS IN HCD

It can now be regarded as reliably established that pumping of the most effective ionic laser transitions of metals mixed with helium in NE HCD is via collisions of the second kind: the Penning process ($He_m^* + M_0 \rightarrow He_0 + M^{+*} + e + \Delta E$) and charge exchange ($He_0^+ + M_0 \rightarrow He_0 + M^{+*} \pm \Delta E$), i.e., reactions with participation of metastable helium (He^*_m) and helium ions, the densities, the densities of which in the plasma is high. The Penning process populates in the cadmium ion transitions with $\lambda = 441.6$ and 325, as against 533.7/537.8 nm, 635.5/636 nm, and several IR transitions, 723.7/728.4 and 806.7 nm by charge exchange. Ionization and excitation of helium into metastable states takes place in a gas discharge at low and medium pressures by collisions between the helium atoms with fast electrons of energy higher than 24.6 eV for ionization and then 19.8 eV for metastables excitation.

In a PC the formation of the electron distribution function in energy (EDFE) is produced by acceleration of thermal electrons (produced by ionization of the gas ions) in a relatively weak electric field (~10 V/sec) under condi-

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tions of continuous energy loss to ionization and excitation, and the EDFE is in this case close to Maxwellian with a fast-electron deficit, In NE HCD, however, the distribution is essentially non-Maxwellian with an excess of fast electrons. The reason is that the bands where the electron acquires energy from the field and where it loses it by collisions are spatially separated. In the former, which is concentrated near the cathode walls by the cathode dark space (CDS), which acts as an external ionizer, the electrons emitted by the cathode acquires an energy as the go through the cathode drop (where the field is $E_{cds} \sim 10^3$-10^4 V/cm) without colliding with the heavy particles, as indicated by the absence of illumination in the CDS (even though the excitation probability exceeds the ionization probability).

EDFE were analyzed in [5-10] and it was found that at high energies the integral EDFE has a peak at an energy $eU_{cds} = eU_0$ belonging to the residual number of electrons that have acquired energy in the CDS but did not collide with the NE; the second "smeared" peak at the energy $eU_0 - \varepsilon_1$ (where ε_1 is the first excitation potential) pertains to electrons undergoing one collision, and goes over smoothly into the "tail" of the EDFE (electrons undergoing several collisions). There is also the most numerous group of thermal or plasma electrons with energy lower than ε_1, produced by ionization of the atoms by fast electrons and not suitable for excitation. The weak electric field in the NE contributes to Maxwellization of these electrons.

This mechanism of EDFE formation in HCD is confirmed by an investigation of the profiles of the spectral lines at various gas pressures [9], which shows that, on the one hand, the number of fast electrons responsible for the ionization and excitation of the helium is decreased as they advance into the NE, and on the other hand are focused in the axial parts of the NE on account of the negative curvature of the emitting surface of the atom. Focusing predominates at low pressure, and the electron density and also the rate of excitation and the intensities of the lines are maximal on the axis. As the helium pressure increases, the electron mean free path in the NE becomes shorter, their number in the axial part is decreased, the excitation-rate profile becomes flat (the helium pressure optimal for lasing), and with further increase a maximum appears at the NE boundaries, i.e., at the walls of the cathode cavity.

The dynamics of the integral EDFE and of the excitation and ionization rates of helium were analyzed in [6] at the helium pressure optimal for lasing and with variation of the metal-vapor pressure, and a comparison was made with the situation in PC. The EDFE and the rate of helium excitation were found to have a weak sensitivity, compared with the PC, to the vapor density. Upon entry of the vapor, this rate is lowered more than 1-2 orders of magnitude more slowly in the HCD than in the PC, and this explains the higher, by 1-2 orders, optimal vapor density in the HCD. In the optimal regime for HCD, at a vapor pressure 10-30 Pa, when the helium ionization and the excitation of the ion lines of the metal in the PC are already totally absent, the number of fast electrons in the PC of the HCD is still sufficiently high, and they still effectively ionize and excite the helium, while the excitation rate is lower than in pure helium by only a factor of 2.

The reason is that formation of EDFE in HCD "from the high-energy side" causes predominant ionization and excitation of the helium by the fast electrons [11], which do not expend their energy on ionization of the metal atoms. The situation is reversed in PC, where the fast electrons that can ionize are produced by acceleration of thermal electrons in the relatively weak PC field, of the order of $E_z \sim$ 10-30 V/cm, when part of the energy acquired by them is constantly lost just to ionization of the metal atoms.

In addition, as the metal vapor density increases, the loss of the number of fast electrons in the NE of the HCD is partially compensated for by an increase of the energy of the primary electrons on account of the increase of eU_0 (while in the PC an increase of the vapor density is accompanied by a decrease of E_z). The experimentally observed increase of U_0 with increase of the vapor density can be explained on the basis of the equation for an independent discharge

$$\sum_i \gamma_i \phi_i N_i = 1 \qquad (1)$$

(where γ is the emission coefficient and $\phi_1 N_1$ is the number, per produced electron, of ions that diffuse from the NE into the CDS), taking into account the replacement of the buffer-gas ions by metal ions. At $U_0 \sim 10^2 10^3$ V we have $\gamma(\mathrm{He}) = 0.25$ and $\gamma(\mathrm{Cd}) = 0.05$, so that replacement of the light helium ions by the heavy metal ions increases the CDS potential needed to maintain the emission [6, 8, 11].

The described mechanism of EDFE formation in HCD ensures, firstly, a higher efficiency of discharge-energy conversion into the energy of the fast electrons capable of ionizing and exciting the helium. Secondly, the higher optimal metal-atom density in the NE of the HCD than in the PC causes a more complete utilization of the energy of the metastable helium atoms and ions in the Penning process, and as a result a higher rate of pumping the ion levels of the metals. The frequencies of the impacts of the second kind exceeds considerably the frequencies of all other processes (diffusion, deactivation by electron impact, etc.). That is to say, the decay of all the helium ions and metastables is effected only by charge exchange and Penning ionization, respectively, while the total rate of pumping to all the metal ion-spectrum levels, populated, e.g., by charge exchange, is equal in the PC of an HCD by the total rate of helium ionization, and not by half this rate as in PC [11]. The same pertains also to Penning ionization. Thus, when the metal atom density in the HCD is increased, the initial growth of the lasing power is determined by the growth of this density; saturation corresponds to complete deactivation of the excited atoms (ions) of the buffer gas on the metal atoms, and the subsequent decrease of the radiation power duplicates exactly the decrease of the rate of buffer-gas excitation by the decrease of the number of fast electrons at excessively high vapor pressures.

Since the buffer-gas ionization, which determines the charge-exchange rate, is provided in final analysis by the energy of the monokinetic group of primary electrons accelerated in the CDS, it is clear that the excitation rate is a growing function of the CDS potential determined by the cathode material [8].

Since the NE plasma contains an appreciable density of slow thermal electrons with energy significantly lower than in the positive column (of the order of several tens of an electron-volts), effective level de-excitation processes take place not only in the "afterglow" of the pulsed discharge, but also during the current pulse, as well as in a stationary discharge. In the latter case, for example, the electron de-excitation of the higher-lying levels determined the pumping of the F−D transitions of Cd II in HCD [12].

Thus, excitation of ionic transitions metals bye impacts of the second kind (charge exchange and the Penning process) is more effective in the PC of a HCD than in the PC of a longitudinal discharge. This is due both to the higher efficiency of discharge-energy conversion first into fast-electron energy and then into energy of metastable helium atoms and helium, and to the higher efficiency of energy transfer from the latter to the ionic laser states.

3. CONSTRUCTION AND CHARACTERISTICS OF THE LASER

The urge to achieve maximum laser power which is simultaneously highly stable has led to the development of numerous designs of lasers with HCD, which can be arbitrarily divided into two large groups with different placements of the electrodes in the tube. In the construction of the first type (which we name transverse) [2, 14] the anode is located along the axis of an extended cathode cavity, so that the electrons and ions move perpendicular to the axis. In the constructions of the second type (so-called longitudinally transverse, and including those with a sectionalized cathode and sectionalized anodes at the ends of the sections, with a cathode of the "flute" type, and many others [13, 15-17]), the electrons emitted by the cathode move in the HCD plasma towards the anode along the cathode cavity. Experience has shown that both constructions are approximately of equal discharge-burning stability (without breaking up the glow discharge into an arc discharge, which determines the lasing stability). Another question, of no less practical significance, is that of the construction that ensures maximum radiation power and efficiency, is being actively discussed of late (see, e.g., [18]), but the conclusions are contradictory. In our opinion the main reason is that experiments with both constructions were carried out under different and nonoptimal discharge conditions, and their results were unjustifiably generalized to the entire region where lasing exists.

We have investigated the inhomogeneity of the discharge-current density along the length of longitudinal−transverse constructions. This inhomogeneity was determined by optical measurement of the intensity of the 471.3-nm helium line (see Fig. 1) populated by direct electron impact, and linearly dependent on the current, with correction for the variation of the form of the EDFE as a function of the CDS voltage U_0 along the section:

$$j(z) \sim I_{471.3nm}(z)/f[U_0(z)]$$

where f is a function reported by us earlier in [8] and representing the dependence of the excitation rate of a given helium line on U_0.

The $U_0(z)$ dependence was determined both by the method of a single electric probe, and by the axial potential drop in the Ne, U_{NG}, measured by the double-probe method and connected with the gradient of the axial field E_{NG}:

$$U_0(z) = U - U_{NG}(z) = U - \int_x^1 E_{NG}(z)dz$$

U is the voltage across the anode−cathode gap.

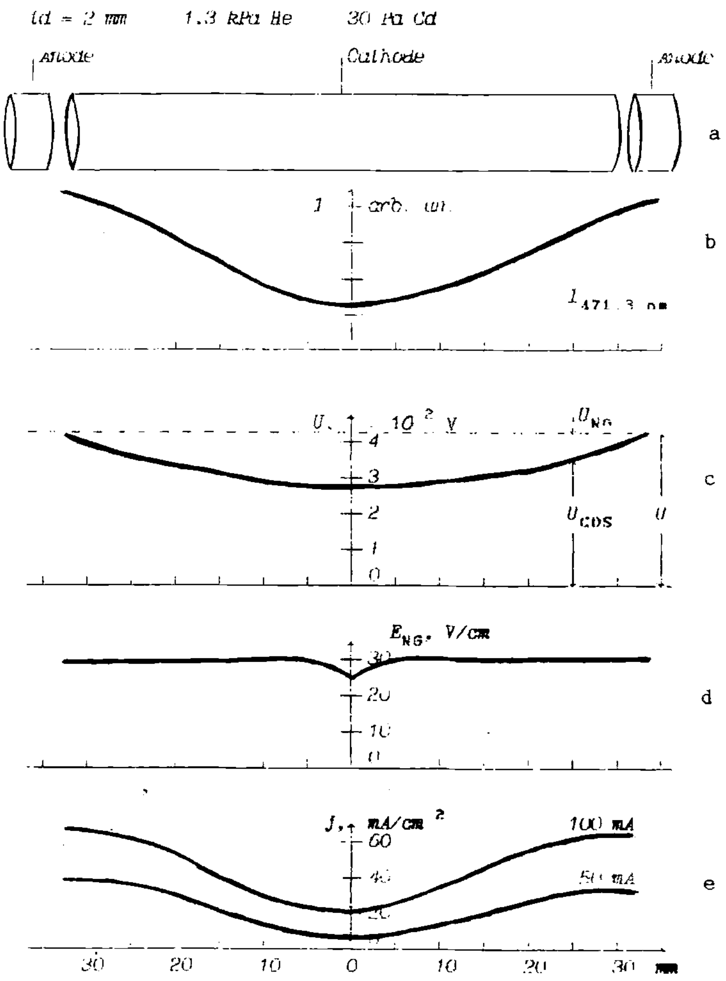

Fig. 1. Electric characteristics of discharge tubes with HCD of longitudinal-transverse type: a) schematic diagram of the electrodes, b) intensity of the 471.3-nm He I line, c) voltage drop on the cathode dark space, U_{CDS}, and on the negative emission, U_{NG}, d) longitudinal-field intensity E_{NG} in the negative glow, d) longitudinal-field strength in the negative glow E_{NG}, e) density j of the current from the cathode surface.

We call attention to the presence of a rather strong field E_{NG} on the cathode axis in the longitudinally transverse construction. The presence of this field is due, in our opinion, to the fact that in the longitudinally transverse construction the transport of charges inside the NE by diffusion only [16] cannot maintain the necessary current density at the anode. Owing to the presence of E_z, as the plasma advances inside the cathode cavity, its potential relative to the cathode, i.e., U_0, decreases. This determines, in accordance with the rising current–voltage characteristic of the CDS, the decrease of the current density on moving into the interior of the cavity.

It cannot be stated, however, as was done in [18], that an HCD plasma of the longitudinal–transverse type comes close to the positive-column plasma, since the discharge self-sustainment mechanism, the electron spectrum in the high-energy region, and also the rates of formation of excited and charged particles, all remain the same as in the NE of a transverse HCD. This is confirmed by the absence of jumps in the intensity ratios of the atomic and ionic lines on going from sections from small E_{NG} to those with large E_{NG}, and, as before, by the anomalously high intensity of the ionic lines of the metal, including also the laser lines, when the vapor pressures are higher by 1-2 orders than the optimal for the positive column, but typical of the CDS NE. Note that along with the nonuniform distribution of the current density in NE of HCD of longitudinal–transverse types, the metal-vapor distribution in the dead-end tubes also becomes inhomogeneous, owing to cataphoresis in the inhomogeneous field E_{NG}.

TABLE 1. Characteristics of Experimental Laser Specimens with HCD

Specimen No.	Active length, cm	Number of discharge sections	Current of one section, mA	Emission power in lines, mW			Noise level, %
				441.6 nm	533.7 537.8 nm	636.0 nm	
1	10	2	100	2*	–	–	< 1
2	40	5	200	45	25	10	< 1
3	80	10	200	115	35	13	< 1

Comparison of the emission powers of discharge tubes with longitudinal–transverse and transverse constructions shows that for most laser lines that grow linearly with increase of current from threshold to saturation, the power in a "purely" transverse construction is approximately 1.8 times higher. The reason is that when the current is low in the longitudinal–transverse construction the contribution of the deeper sections of the cathode, where the current density is lower than or close to threshold, and when the current is high the contribution of the sections nearest to the anode, where the current density becomes higher than the optimal, and is also caused by nonuniform axial distribution of the vapor density. The efficiency is also higher (by 1.3-1.5 times for different lines). The longitudinally transverse construction is superior to the transverse only at low current and for those laser lines on which the power increase is faster than linear. It is only in such a nonoptimal regime that the measurements of [18] were made, but the conclusion that the longitudinally transverse construction is superior was incorrectly generalized. In addition, the complete absence of a longitudinal electric-field component in the NE of the transverse HCD should not lead to distortion of the spectral-line contours, an important factor in metrological applications.

Our "purely" transverse laser construction with a HCD is superior to the longitudinally transverse one with respect to most parameters. The prospect of increasing the emission power is directly connected with advances into the region of increased discharge-current densities, where the transverse construction can be seen to have the advantage.

Production of an axially extended and geometrically uniform cathode cavity in a discharge tube, as well as sectionalization of the anode, make it possible to construct a tube of desired active length to achieve the necessary power, mode makeup of the radiation, etc.

We have produced experimental tube specimens with active lengths 10, 40, and 80 cm. The tube dimensions and the discharge parameters are listed in Table 1, analysis of which shows that a laser with HCD is substantially superior to a cataphoresis laser with PC excitation. The superiority lies, first of all in the number of laser lines, since it has a set of three reference colors – blue, green, and red; secondly, in the running power of the radiation (up to 200 mW/m compared with the typical 40-50 mW/m for cataphoresis lasers operating on only one line in the visible band – 441.6 nm), and thirdly in the emission noise level (less than 1 rms compared with the typical 5-10% of cataphoresis lasers).

4. ENERGY AND SPECTRAL CHARACTERISTICS OF EMISSION

Table 1 lists the discharge conditions corresponding to different operating regimes of a cadmium-vapor ion laser with a discharge of "purely" transverse type, viz., maximum power on each line, equal powers in each color, and maximum total power for three-color emission. Data are also given for a mixture of helium with mercury vapor, emitting the intense 615.0-nm red line of the mercury ion [23]. The use of a helium + cadmium vapor + mercury vapor mixture requires some modification of the construction. It makes possible, on the other hand, by "replacing" the red cadmium-ion line by the red mercury-ion line, to increase by an order of magnitude the power in the red region of the spectrum, thereby bringing the power ratio closer to the natural "white" light.

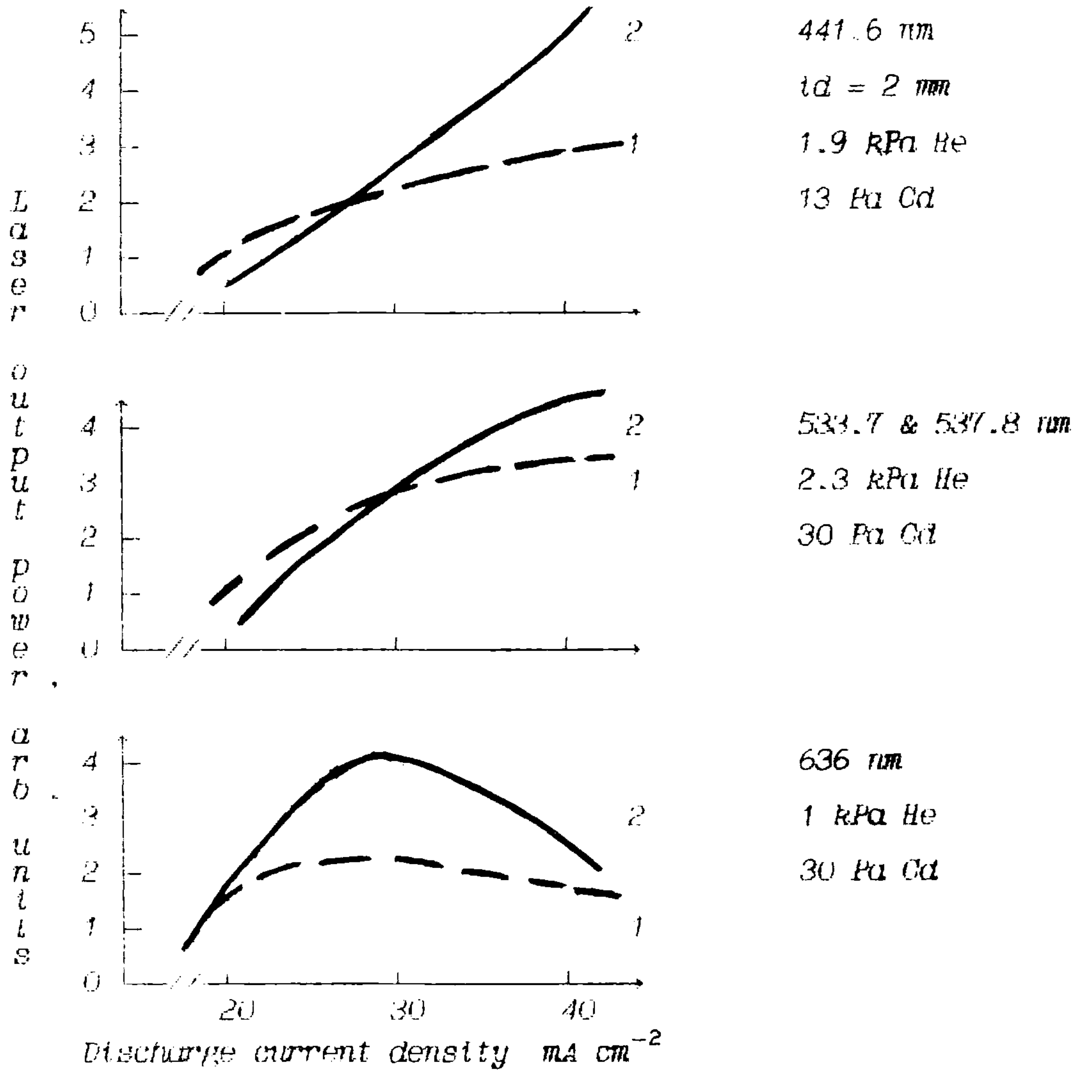

Fig. 2

Simultaneous emission on all lines corresponds to a pressure range 8-20 kPa. The discharge current-density range for joint lasing on the cadmium lines is 5-40 mA/cm^2, and on the blue and green cadmium lines and the red mercury line – more than 40 kA/cm^2. The optimal discharge conditions in the different regimes are given in Table 2.

A remarkable feature of lasers with HCD is the longer-lived stability and the low radiation noise: the former is determined by the presence of a massive metallic shell of the discharge tube, which ensures uniform tube heating and prevents cadmium neutral-atom density fluctuations due to condensation and sublimation of the metal from the cathode surface.

The HCD-laser emission spectrum contains no high-frequency discrete components; this is the principal feature of the HCD compared with the PC. It is known [26] that the noise source are reactive oscillations in the plasma as well as stratum waves of varying frequency, resulting from the presence of an axial electric field and amplified by Penning ionization of the mixture. In a plasma of a NE HCD of the longitudinal–transverse type the axial field is much weaker, and is zero in a "purely" transverse construction. The absence of reactive oscillations in HCD is apparently caused also by the positive impedance of the discharge gap.

Another parameter of importance in applications is coherence of the laser emission. The coherence length was measured using a Michelson interferometer with variable arm length and amounted in the one-mode regime to 4.5 m for the green and red lines, and 0.8 m for the blue. The emission spectrum widths of these lines, estimated on this basis, do

TABLE 2. Optimal Discharge Conditions and Specific Emission Power in HCD (for tube No. 2)

Active medium	Wavelength, nm	Metal vapor pressure, Pa	Helium pressure, kPa	Cathode current density, mA/cm^2
Separate lasing regime				
He-Cd$^+$	441.6	13	1.9	56
He-Cd$^+$	533.7 537.8	30	2.3	40
He-Cd$^+$	836.0	30	1.0	30
He-Hg$^+$	615.0	40	1.7	250
Joint lasing regime with equal powers (blue:green:yellow = 1:1:1)				
He-Cd$^+$	441.6 533.7/537.8 636.0	30	1.1	10
He-Cd$^+$-Hg$^+$	441.6 533.7/537.8 615.0	13(Cd) 5(Hg)	2.7	40
Joint lasing regime with maximum total power (blue:green:red = 14:7:1)				
He-Cd$^+$	441.6 533.7/537.8 636.0	13	1.3	40

not exceed 30 and 190 MHz respectively, and when the intermode gap is taken into account (of order 100-150 MHz in different versions) it can be concluded that lasing in the red and green lines is in a single-frequency regime, owing to the strong Lorentz broadening of the lines.

Since an He–Cd$^+$ laser with HCD generates three reference colors – blue, green, and red – covering the entire range of color reproduction, it can replace successfully several lasers each generating one line (for example, helium – neon red, argon blue-green, and helium – cadmium cataphoresis blue). Since all three emissions of a laser with HCD are directed along one optical axis, the optical system for the processing of the emission is several times simpler than that necessary to combine the emissions of three lasers into a single beam.

Analysis of the world market and its growth tendencies, based on information in [32], shows that an He–Cd$^+$ laser with HCD will be able in the near future to compete, and in part also supplant the presently available lasers in applications such as:

– various devices for the analysis and recording and color images on various media such as: copying motion-picture film on video cassettes and vice versa, copying from ordinary motion-picture and other photographs to higher-resolution materials;

– laser printers, laser displays;

– multicolor holography, multicolor lithography;

– multicolor glass – interferometry;

– devices for demonstration of visual and optical effects, etc.

Recognizing that HCD laser emission lines are distributed fairly uniformly over the spectrum, with approximate intervals 100 nm, one can propose to use the laser for various multicolor measuring devices, to monitor light-sensitive and other materials, in metrology, in laser microscopy, etc. Its use may be promising in medicine, for example in photodynamic therapy for analysis of liquid biological components.

Obviously, the most attractive is the use of a helium–cadmium laser with HCD in the multicolor operating regime. However, even when working with the most intense blue line, however, such a laser can be used more effectively than a cataphoretic one with excitation in a positive column.

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