KWARTAL NIK ELEKTRONIKI I TELEKOMUNIKACJI, 1997, 43, z. 1,ss. 99–108

Infrared laser properties of sputtered He–Cu mixtures excited by radio-frequency and hollow-cathode discharges

TADEUSZ M. ADAMOWICZ

Instytut Mikroelektroniki i Optoelektroniki, Politechnika Warszawska

MIECZYSŁAW KOCIK, JERZY MIZERACZYK

Instytut Maszyn Przepływowych, Polska Akademia Nauk, Gdańsk

JÜRGEN MENTEL

Allgemeine Elektrotechnik und Elektrooptik, Ruhr-Univerity, Bohum

Received 1997.02.12

Authorized 1997.04.20

Laser action on Cu II $\lambda = 780.8$ nm line in sputtered He–Cu mixtures excited by radio-frequency discharge is reported. The threshold power ot the laser operation has been as low as 20W per unit length of the discharge. Small-signal gain measured in media excited by a conventional hollow cathode and an RF discharge shows close resemblance for both kind of excitation. For similar cross-sections of the discharge the gain coefficients are similar at the same linear densities of the discharge power. For the RF excitation the gain coefficient exceeding 20%/m has been obtained at 240 W/cm.

Key words: RF, hollow-cathode discharge, metal ion laser, sputtering, laser gain

1. INTRODUCTION

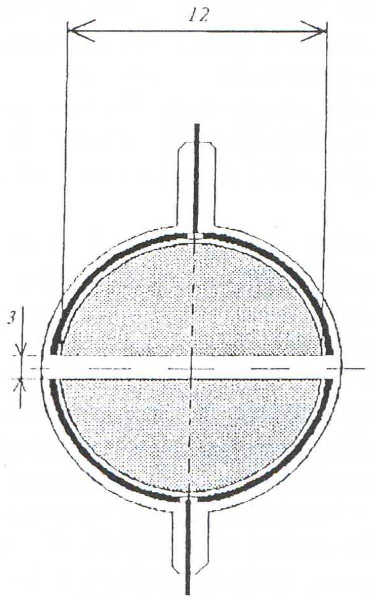
For more than two decades laser transitions have been detected in discharges produced in several metal vapour-noble gas mixtures, [1–2]. In this kind of lasers population inversion between excited states of singly ionised metal ions is achieved by the thermal energy charge- transfer reaction between metal atoms and ground state noble gas ions. The charge-transfer reaction occurs effectively in a hollow cathode discharge, (HCD) where large numbers of fast electrons oscillating between the opposite walls of the cathode produce a high density of the noble (buffer) gas ions and the necessary density of metal atoms is obtained by cathode sputtering. Such metals as Ag, Au and Cu which cannot be easily evaporated are efficiently sputtered by ion bombardment of the cathode walls. For each of them, using He or Ne as the buffer gas, strong laser lines covering the spectral range from 220 nm to near infra-red have been reported, [3–5]. Despite many attempts the efficient and cheap UV HCD lasers operating in CW or long pulse mode have not yet been constructed, mainly due to a discharge instability, so called arcing. An alternative to the HCD excitation of the sputtered metal vapour-noble gas systems is a radio-frequency, (RF) discharge. The RF excitation widely used in modern waveguide CO_2 lasers, has been successfully applied to other noble gas-metal vapour and noble gas mixture systems like $He-Cd^+$, $He-Se^+$ and $He-Kr^+$ [6, 7]. Both the HCD and RF discharges show much similarity in assuring very effective ionisation within the discharge volume. However, the later is more advantageous in producing stable and uniform discharge plasma. The laser oscillations on an infra-red line in a sputtered He–Cu mixture excited by the RF discharge were first reported in [8], but no further attempts were made to optimise the discharge and generation conditions.

In this paper we present the results of our study of lasing features, i.e. laser action and unsaturated gain in sputtered He–Cu mixtures excited by capacitively coupled radio-frequency (CCRF) and conventional hollow-cathode discharges. Our measurements have been carried out for the strongest Cu II laser line, $\lambda = 780.8$ nm. The small-signal gain obtained for the RF excitation is compared with the gain measured for two types of hollow cathodes with similar discharge cross-sections areas.

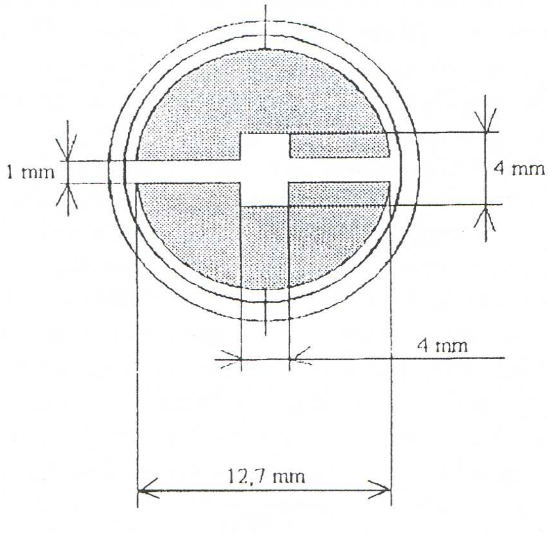
The ultimate aim of our researches is collecting the necessary data for the future investigations of UV operating lasers excited by the RF discharge.

2. EXPERIMENTAL

We used two different configurations of discharge tubes to investigate the laser action in sputtered He–Cu mixtures excited by the RF discharge. The first one was provided with a pair of oxygen-free copper electrodes in the form of half-solid cylinders placed parallel to each other and 3 mm apart. The length of each electyrode was 40 cm. The cylindrical parts of the electrodes were enveloped with fused silica glass half-cylinders to prevent the RF discharge outside the volume between the flat surfaces of the electrodes. The cross-section of the discharge gap was 3 × 12 mm, as it can be seen in Fig. 1a. In the second laser tube the 20 cm long



1a.



1b.

Fig. 1. The cross-sections of the discharge gap in an RF excited laser tubes

electrode set was also formed by two half-solid copper cylinders placed only 1 mm apart, but along the flat side of each electrode a 4 × 1.5 mm slot was cut. Therefore, the RF discharge cavity cross-section was 4 × 4 mm, — Fig. 1b.

Before mounting into the laser tubes the copper electrodes were treated chemically and for about 30 hours heated in the vacuum up to 700 – 800 C. In the laser tubes the electrodes were heated inductively again until the pressure in the vacuum system was better than 10^{-6} mbar.

The discharge tubes were filled with He+Ar mixtures. A small amount of Ar (1 – 3%) was used to enhance the discharge sputtering of the copper electrodes. The electrical power was delivered to the discharges through a matching network from RF generators operating at 13.56 and 1.96 MHz, respectively. The matching network which was tuned at each power level, buffer gas pressure and configuration of the electrodes. An RF power meter capable of measuring the forward and reflected power enabled us to establish the amount of the RF power delivered to the discharge. An optical resonator was formed by two identical, almost fully reflective IR laser mirrors with curvature radius 1.5 m and separated by a distance of 70 cm.

Small-signal gain of the lasing media excited either by the RF discharge or by the hollow cathode discharges with similar discharge cross-sections was measured using a method described in [9]. The idea of the method which enables to compare the lasing features of active media created in different kind of discharges is shown in Fig. 2. In the present study, two independently excited lasing systems were aligned on the same axis in a dismountable laser tube ended with the Brewster windows. The first was created in a 10 cm long and 3 mm inner diamter helical hollow cathode discharge and served as the laser-oscillator for a medium which gain was to be measured. The amplifying RF discharge sets were 10 and 5 cm in the length, respectively. The shortening of the electrodes length was due to increased density of the RF discharge power per unit of length. The discharge cross-section equal to 4 × 4 mm was almost identical as in Fig. 1b. The only difference was that a distance between flat surfaces of half-cylinders was 0.5 mm and the outer parts of electrodes were enveloped by an alumina ceramic tube instead of quartz. The hollow cathode discharge sets were as follows: a 9.5 cm long rectangular slotted HC with the cross-section of 4 × 6 mm, and 10 cm long, 4 mm ID helical HC wound from 2 mm wire and with 3 mm pitch. The outer surfaces of the cathodes were covered by high purity alumina tubes provided with about a 4 mm slot facing an anode. The anode was made of 4 mm stainless steel rod placed parallel and about 5 mm above the cathode openings. The amplifying sets were successively connected to the special mounting inside of the laser tube which enabled movements in two directions perpendicularly to the axis of the laser resonator.

The laser tube and the optical attenuator were placed into a symmetrical 1 m long resonator consisting of two identical mirrors in such a way that the waist of the laser beam was situated in the middle of the investigated discharge. The proper positioning of the path of the laser-oscillator beam inside

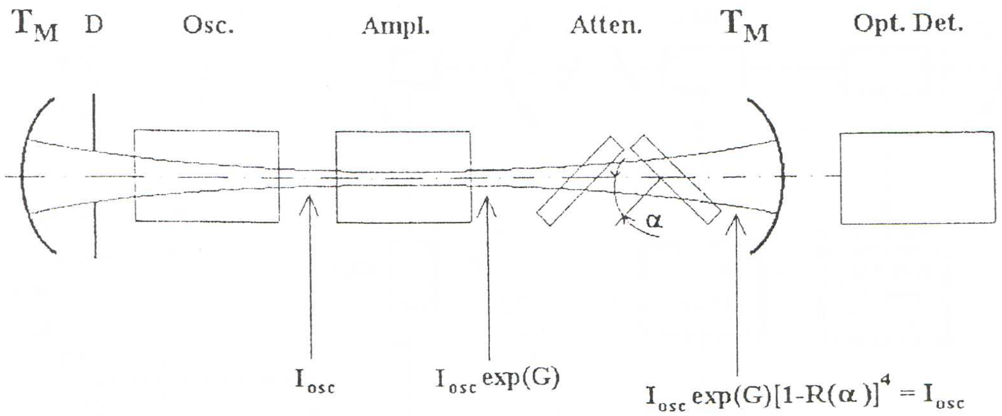


Fig. 2. The principle of the method of gain measuring. For G and $R \ll 1$, $G \cong 4R\alpha$)

the amplifying medium was essential for in sputtered HCD lasers a spatial distribution of gain was found to be highly non-uniform, [10]. In the present case all gain measurements were carried out for the centre of the investigated discharges and for the same shape of the laser beam.

Unsaturated gain in the HCD systems was measured in the following way: both sets, i.e. the oscillator and one of tested HC, were synchronically excited by similar in shape and relatively long (about 1.5 ms) discharge current pulses with 1 Hz repetition rate to avoid overheating. With minimal optical losses the laser-oscillator was brought to the threshold of the laser operation. That meant the gain equalised the constant losses in the resonator cavity. The excitation of the amplifying medium enhanced the laser output power, which was reduced again to the threshold by increasing the calibrated losses. For $G \ll 1$, the additional losses were equal to the unsaturated gain in the medium.

In the case of the RF excited medium, the 13.56 MHz generator, the same as used for laser power measurements, was locked on the pulse mode operation delivering a train of rectangular 2 ms pulses with 1 Hz repetition rate. The excitation of the oscillator was steered by a trigger delay circuit set on 0.5 ms delay time. As the laser action appeared also about 0.5 ms after beginning of the oscillator discharge pulse, the scanning laser beam passed through investigated medium approximately in the middle of the RF excitation period. Hence, the sputtered copper atoms could easily diffuse to the centre of the discharge. An anti-interference filter had to be used to clean a photodetector signal from the RF noises. The block scheme of the measuring arrangement is shown in Fig. 3.

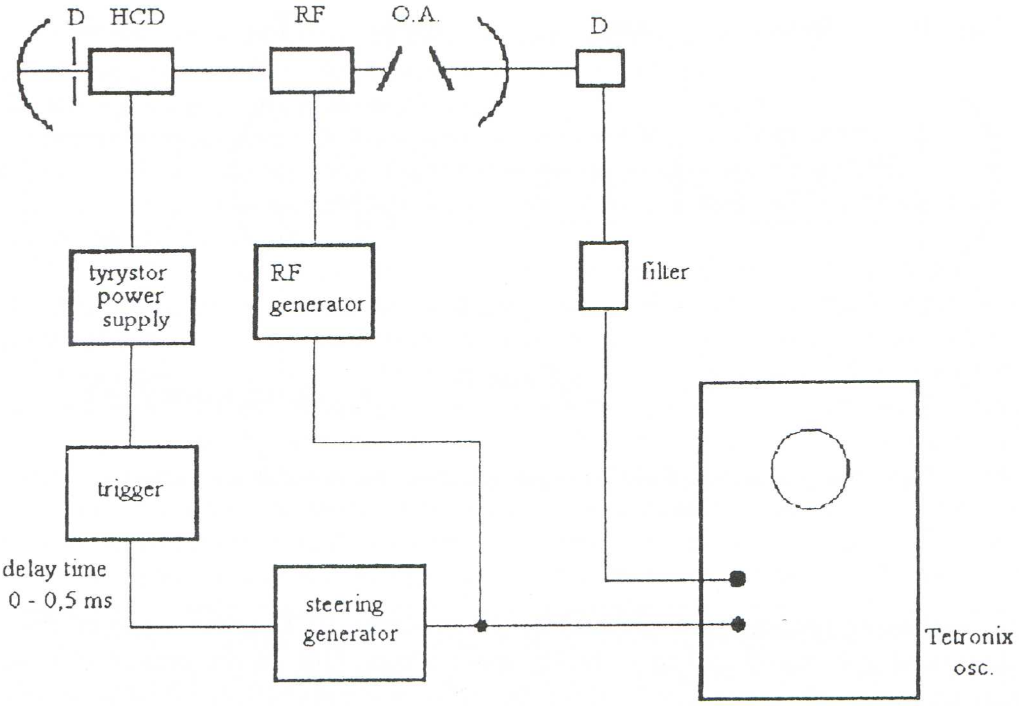


Fig. 3. The block scheme of the arragement for gain measuring in RF excited media

3. RESULTS AND DISCUSSION

We achieved laser oscillations on the Cu II line $\lambda = 780.8$ nm for both laser tube designs when He+Ar mixtures were excited by 13.56, and additionally by 1.96 MHz RF generators. The presented results were obtained for the 13.56 MHz frequency genrator. However, a higher laser output power was observed at 1.96 MHz. In our opinion, the discharge gap geometry as well as the frequency of the RF excitation play the important role in producing the necessary density of sputtered metal atoms. In contrary to the transverse RF discharge excitation used in CO_2 lasers, [11], in sputtered metal vapour- noble gas lasers the main attempt has to be put on a proper balance of the RF discharge power dissipated within the electrode sheet regions and the plasma glow region instead of the glow only.

For the 3 × 12 mm discharge gap tube the laser output power versus pressure of the He+Ar (99:1) mixture is shown in Fig. 4. The optimum operating pressure of about 16 mbar agrees well with the results obtained for 3 mm slotted and helical hollow cathodes in [12]. That geometry privileged the oscillations on higher-order laser modes and the mode structures changed with the buffer gas pressure as it can be seen in Fig. 5. This means the diffusion of sputtered copper atoms into the laser

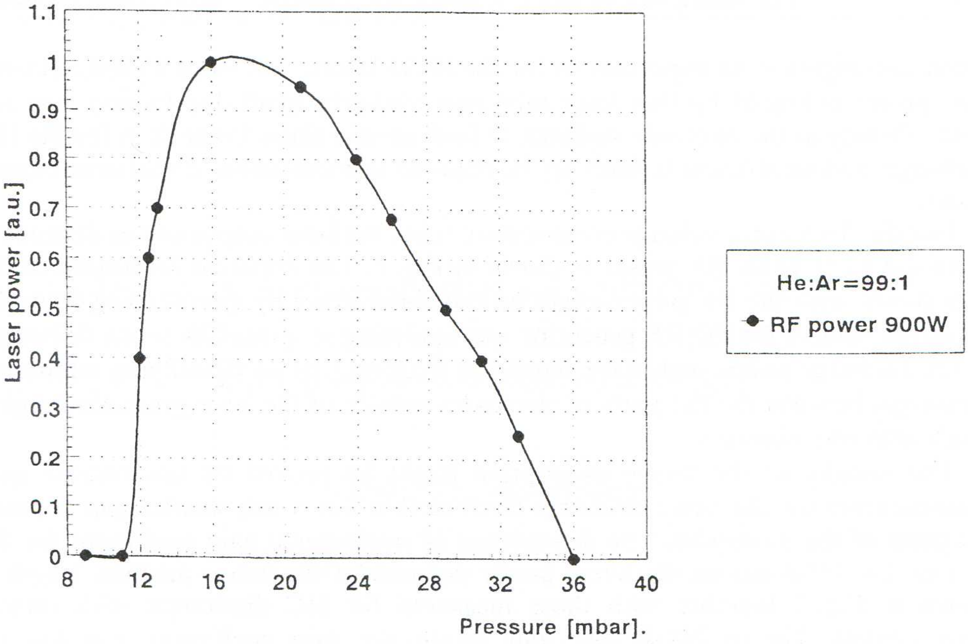


Fig. 4. The infrared 780.8 nm laser output power vs. buffer gas pressure (He:Ar = 99:1) for the 3 × 12 mm discharge cross-section tube. The RF power was 900 W

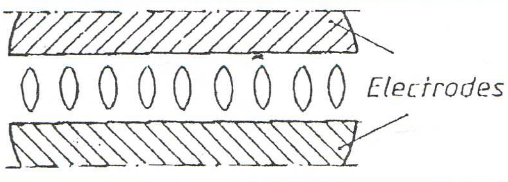
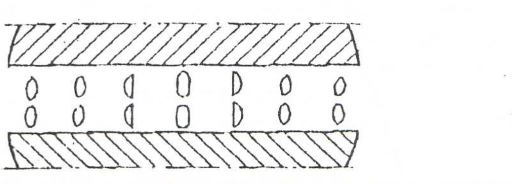
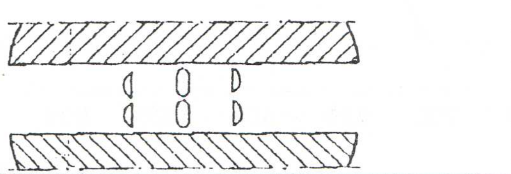
He : Ar pressure mbar	The laser mode (schematically)
12 – 20	
26	
29	

Fig. 5. Typical high-order modes of the He-Cu$^+$ oscillations for different pressures of He:Ar mixture. The RF power was 900 W

generation region is as important as for the HCD lasers. The value of the infra-red laser power delivered by that laser tube was relatively small due to very low RF power density at the electrode surfaces, at least several times lower than for the HC discharge, and insufficient to built up the required concentration of sputtered copper atoms.

For the 4 × 4 mm discharge cross-section tube, the laser output power dependency on the 13.56 MHz RF power is shown in Fig. 6. The apparent saturation of the laser power with the RF power might be explained either by gas escaping from the discharge volume for the RF generator was operating in quasi-CW mode delivering 16 ms discharge pulses with 9 Hz repetition frequency or by developing additional discharges between the flat parts of electrodes outside of the laser generation region which also was observed.

The validity of the above assumption might be proved by unsaturated gain measurements for the same discharge cross-section but much smaller gap between flat parts of the electrodes. The dependency of small-signal gain coefficient for the IR line $\lambda = 780.8$ nm on discharge power per unit of the active medium length is shown in Fig. 7 together with those measured for HC discharges with similar cross-sections. Up to 240 W per unit length the gain coefficient was linearly increasing with the discharge power and followed closely the results obtained for the HC discharges. All gain measurements were carried out for almost the same buffer

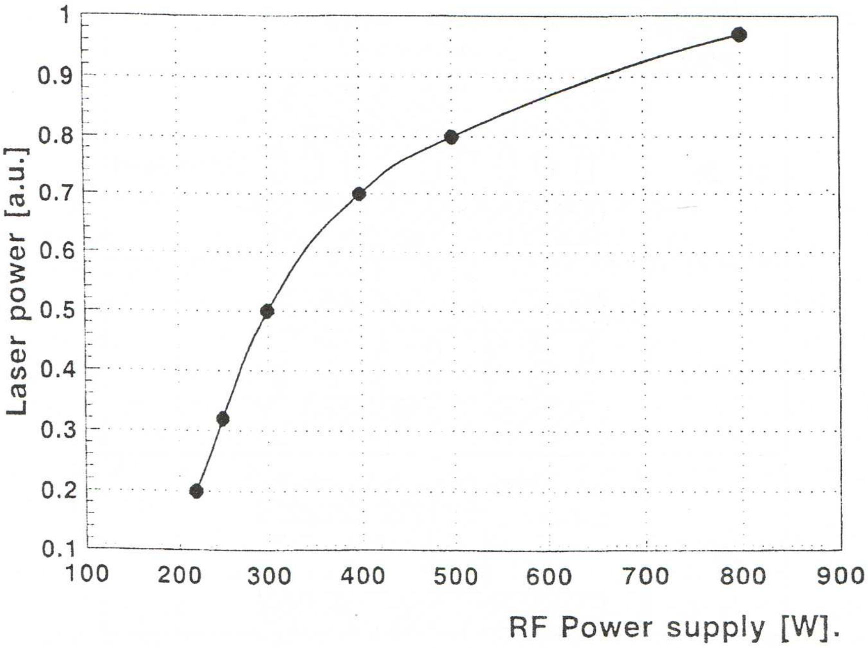


Fig. 6. The infra-red laser output power vs. RF power for the 4 × 4 mm discharge cross-section tube. Buffer gas (He:Ar = 80:1) pressure 16 mbar

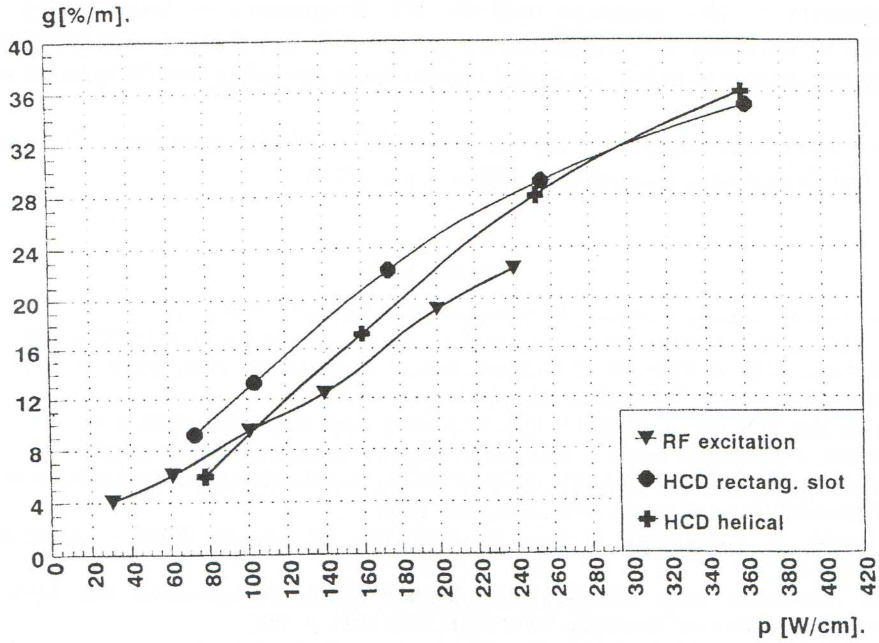


Fig. 7. Unsaturated gain coefficients vs. linear density of discharge power for 4 × 4 mm RF excited medium, 4 × 6 mm rectangular slotted HC and 4 mm ID helical HC

gas pressure in the range of 13 – 14 mbar which was optimal for the investigated media, however, the optimum ratio of He:Ar mixtures was different for each geometry. For the rectangular slotted cathode it was found to be 80:1, for the helical cathode — 60:1, and for the RF excitation about 30:1. That means in the RF excited noble gas-metal vapour systems the sputtering ability of the discharge must be enhanced, e.g. by increasing admixture of heavier noble gases.

SUMMARY

The employing of the RF excitation resulted in the laser oscillations at the Cu ion transition $\lambda = 780.8$ nm in sputtered He – Cu^+ lasers. We were able to achieve the laser action for the 3 × 12 mm discharge configuration with as low as 20 W/cm linear power density, and for which the abnormal glow discharge, short of arcing, was insufficient to bring the laser into operation. However, the RF excited media show close resemblance to the conventional HC discharges, i.e. the operating pressures for the both investigated followed the patterns typical for sputtered HCD lasers. The enhancement of the laser power observed at the lower RF generator frequency and the necessity to increase the argon admixture for the 4 × 4 mm cross-section indicated that the sputtering capability of the RF discharge was lower than that for the HC discharges. We believe, this problem can be solved by adjusting

the geometry of the discharge and the RF frequencies to increase the power delivered to the electrode voltage drop regions. With this done it is possible to built an efficient sputtered noble gas-metal vapour laser operating in UV spectral region.

This work was supported by the Commision of the European Communities under the Copernicus Programme, CIPA-CT93-0219

REFERENCE

1. L. Csillag, M. Janossy, K. Rozsa, M. Salomon: Phys. Lett 1974, 50A, p. 13
2. J.R. McNeil, G.J. Collins, K.B. Perssen, D.L. Franzen: Appl. Phys. Lett. 1975, 27, p. 595
3. R. Solanki, W.M. Jr. Fairbank, G.J. Collins: IEEE J. Quant. Electr. 1980, QE-16, p. 1292
4. K. Jain, S.A. Newton: Appl. Phys. B 26, 1981, p. 43
5. H.J. Eichler, H. Koch, R. Molt, J.L. Qiu, W. Martin: Appl. Phys. 1981, B 26, p. 49
6. N. Reich, J. Mentel, G. Jacob, J. Mizeraczyk: Appl. Phys. Letters, 1994. 64, p. 397
7. J. Mizeraczyk: *Laser Technology* IV: *Research Trends, Instrumentation and Application in Metrology and Material Processing*, Proc. SPIE 1995, 2202, p. 98
8. E. Latush, V. Mikhalevskii, G. Sem, G. Tolmachev, W. Khasiev: Pisma v Zh. Eksp. Teor. Fiz. 1976, 24, 81
9. T.M. Adamowicz: *Laser Technology* IV: *Research Trends, Instrumentation and Application in Metrology and Material Processing*. Proc. SPIE 2202, 1995, p. 302
10. T.M. Adamowicz, F.E.G. Rodenburg: XII *European Sectional Conference on the Atomic and Molecular Physics of Ionized Gases*. ESCAMPIG-XII Proceedings, p. 268, 23–26.08.1994, Noordwijkerhout, The Netherlands
11. P. Vitruk, H.J. Baker, D.R. Hall: IEEE J. Quant. Electr. 1994, QE-30, p. 1623
12. T.M. Adamowicz, J. Groszyk, F.E.G. Rodenburg: Laser Technology IV: *Research Trends, Instrumentation and Application in Metrology and Material Processing*, Proc. SPIE 1995, 2202, p. 307

T.M. ADAMOWICZ, M. KOCIK, J. MIZERACZYK, J. MENTEL

WŁASNOŚCI LASERÓW PODCZERWIENI W ROZPYLANYCH MIESZANINACH He–Cu PRZY POBUDZANIU WYŁADOWANIEM WIELKIEJ CZĘSTOTLIWOŚCI

Streszczenie

W artykule przedstawiono wyniki badań generacji laserowej dla przejścia $\lambda = 780{,}8$ nm w mieszaninach He i rozpylonych w wyładowaniu atomów Cu przy pobudzaniu wyładowaniem wielkiej częstotliwości. Próg akcji laserowej osiągnięto już dla mocy 20 W na jednostkę długosci wyładowania. Pomiary wzmocnienia nienasyconego w wyładowaniu wielkiej częstoptliwosci i dla konwencjonalnego wyładowania wnękowego wykazały znaczne podobieństwo obu ośrodkow laserujących. Dla podobnych rozmiarów poprzecznych ośrodka laserującego i tej samej gęstosci mocy, współczynniki wzmocnienia są podobne dla obu typów pobudzania. W wyładowaniu w.cz. osiągnięto współczynnik wzmocnienia przekraczający 20%/m dla liniowej gęstości mocy 240 W/cm.

Słowa kluczowe: lasery, rozpylanie w.cz. współczynniki wzmocnienia.