Journal of the Optical Society of Korea
Vol. 12, No. 1, March 2008, pp. 31-37

DOI: 10.3807/JOSK.2008.12.1.031

Two Versions of He-Ne Laser 3.39 μm with Radio Frequency Excitation

Mirosław Kopica

Institute of Optoelectronics, Military University of Technology 00-908 Warsaw, 2 Kaliskiego Str., Warsaw, Poland

Jong-Woon Choi*

Department of Information and Communication, Honam University Seobongdong 59-1, Gwangsangu, Gwangju 506-714 Korea

(Received December 11, 2007 : revised March 3, 2008)

To increase output power of a He-Ne laser we propose to use the capacitive rf discharge and implement four channel structure. Most of experiments were carried out with a single laser tube from this structure to optimize the output mirror transmission, pressure and composition of the mixture. A laser tube of 2.8 mm inner diameter and 50 cm discharge length can give an output power of above 5.5 mW at 3.39 μm. Four such tubes in "matrix" structure let us obtain 20 mW of output. Simplified models which can be used to evaluate the behavior of an equivalent electrical circuit with laser plasma and qualitative characteristics of output power of He-Ne laser were also described.

OCIS codes : 140.0140, 140.1340, 140.3410

I. INTRODUCTION

The He-Ne laser (together with CO_2) is certainly the most popular of gas lasers. It can oscillate on many wavelengths, from visible to infrared. Moreover low cost, long lifetime, and simple structure have suited them for a great variety of applications, e.g., in metrology, holography, spectroscopy, and medicine even though the He-Ne laser is a typical low-power device [1]. But sometimes higher power is required as in the case of photodynamic therapy for cancer (more than 0.1 W at 633 nm) [2] or for remote detection of methane (3.39 μm) where the measurement range and sensitivity are functions of laser power. Conventional He-Ne lasers are excited by a longitudinal dc discharge in a tube, the tube having an optimal radius for this laser. Under optimized conditions, the available output power at the 633 nm transition may range from 1 to 10 mW for tube lengths from 20-50 cm and 10 to 20 mW for 100-200 cm lengths of tubes at the 3.39 μm [3]. The volume and power can be increased by making the cross section elliptical or rectangular. A He-Ne laser tube with a cross section of 20×4.5 mm and a discharge length of 1.7 m can give an output power above 200 mW [2, 4]. Recently, the study and calculations of performance of a laser having an annular gain zone with the multi-pass ring resonator has proved that a 1 W output can be obtained from a 1 m length annular discharge structure (λ = 633 nm) [5].

Now, many problems with gas lasers are solved by use of transverse radio-frequency (rf) gas discharges for excitation. For example in the case of CO_2 lasers more than a half of the word's commercial devices operate on rf discharge with power levels from a few Watts to 10 kW. It is well known that the first He-Ne and CO_2 lasers (in the 1960s) were pumped by longitudinal rf discharge. However, because of some disadvantages such as local overheating of the laser tube near the electrodes, considerable longitudinal inhomogeneity of the discharge etc., this kind of excitation was replaced by pumping with dc discharge. Renewed interest in the pumping of helium-neon lasers with a transverse rf excited discharge were reported in the 1970s by groups mainly from the former Soviet Union. Muller et al. (1979, 1981) [6, 7] reported that the laser output increased steadily with pumping frequency up to 900 MHz, the highest frequency they tried. The measured laser gain was found to be about 50% greater than for dc at optimum. However, in another independent study the laser output power was optimized with a pump frequency of 420 MHz, and it was comparable with that obtained for dc [8]. Andrews and King (1989) [9, 10] investigated the influence of electron energy distribution on laser performance under rf excitation in the range 200-2000 MHz. An enhancement in optimum gain of 20-30% over dc excitation for a He-Ne laser has been verified in an experimental study. They observed an output power from a 3.5 mm diameter laser filled with a 9:1 He-Ne mixture at 1.5 Torr total pressure and suggested the optimum frequency to be about 1000 MHz. To increase power of the 633 nm laser, Glebov et al. (1997) [11] proposed to use the combined pumping (dc and inductive rf discharges), for realization of the homogeneous excitation of the active medium in coaxial geometry. Their calculations determined the specific output power of 0.5-1 W/m on the length.

As mentioned above, for some applications of He-Ne laser, the increasing of power is important and necessary. If we would like to use its two lines from the infrared range, e.g. 3.3922 μm and 3.3912 μm for remote detection of methane on distances up to 100 m, it is important to increase the laser power to 40 mW [12]. Although on the market there are lasers offered with power of 10-20 mW (at a length of 1-2 m), however their dimensions and weight are not encouraged [3]. For such an application not only is the output power essential but also compactness and reliability. In this case the pulse regime of the laser source is important. To build such a source we proposed making use of the advantages of rf discharge and a four channel structure of active medium [13]. In the article, we report on the practical realization of that proposal and the preliminarily results of optimization.

II. SELECTION OF LASER HEADS AND PARAMETERS

There are two main ways of gaining laser power in a typical tube He-Ne system. One way is to increase the tube length by connecting many of them in series to the resonator, the other way is to use many parallel tubes to a common resonator. Both of them are employed in practice. Each construction has its own drawbacks, especially when dc discharge is used. The multi-channel idea for diffusion-cooled CO_2 lasers with rf excitation, in which many individual tubes are connected in parallel to a common resonator was built also. In these cases laser beams are optically independent of each other. However, the laser modules can be optically coupled and generate coherent radiation. Various ways of coupling and stabilizing coherent modes have been suggested and built, especially for CO_2 lasers. There have been many suggestions to implement such solutions for He-Ne lasers, also with slab or annular constructions [5, 14].

We have decided to build our laser on the basis of a glass tube with metal electrodes outside and connect four such tubes to a resonator (Fig. 1). We name this structure a "matrix laser". The idea was applied earlier for a CO_2 laser [15]. Due to the four identical glass tubes and the fact that they are filled from one ballast container, it is better and easier to carry out the experiments with one tube. The results would be scaled for four channel construction which also has the similar electrical scheme (Fig. 3). The single tube with a proper resonator can work as an independent laser as well.

In general, the experimental optimization of the laser discharge gain medium aimed at maximizing the laser power extraction involves many intrinsic and extrinsic factors. The study of the parametric dependencies or scaling laws, as applied to lasers based on dc longitudinal glow discharges in dielectric tubes, has received considerable attention in the literature [16]. For the case of the diffusion-cooled gas lasers excited by the longitudinal dc glow discharges, it was found that the main invariants are as follows: electron temperature T_e, reduced electric field in the plasma E/p, the product pD of gas pressure p and tube diameter D, the ratio j/p of the discharge current density j and the pressure, and the ratio P_{out}/L of the output power P_{out} and the tube length L. Compare to dc discharge lasers, the optimization of lasers with rf excitation is rather more complicated, but potentially more efficient, because of an additional parameter of choice - the frequency f of the rf generator. The possibility of regulating plasma parameters by choosing the frequency is an essential advantage of rf laser excitation. For waveguide CO_2 laser, during investigations over a range of excitation frequencies of 100-160 MHz, for gas pressures of 40-100 Torr and for inter-electrode distances of 1-3 mm in a typical gas mixture, the additional scaling law fD = constant was established. The analysis indicated both high- and low-frequency limits to the operation of such lasers. In addition, the data indicate that for rf-excited lasers over a wide range of experimental conditions a relationship pD = constant is applicable [16]. In the case of He-Ne dc excited lasers it is well known that for the partial pressure of He and Ne of ~ 5:1 at λ = 632.8 nm the optimum value of product pD is 3.6-4

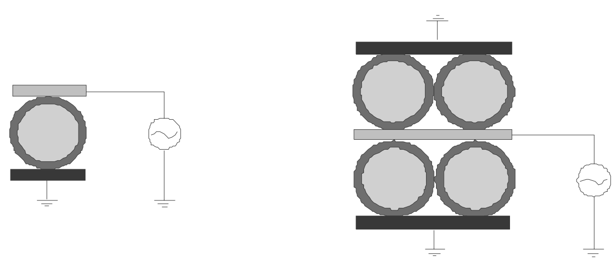


FIG. 1. Geometry of the laser heads: (a) single structure, (b) matrix construction.

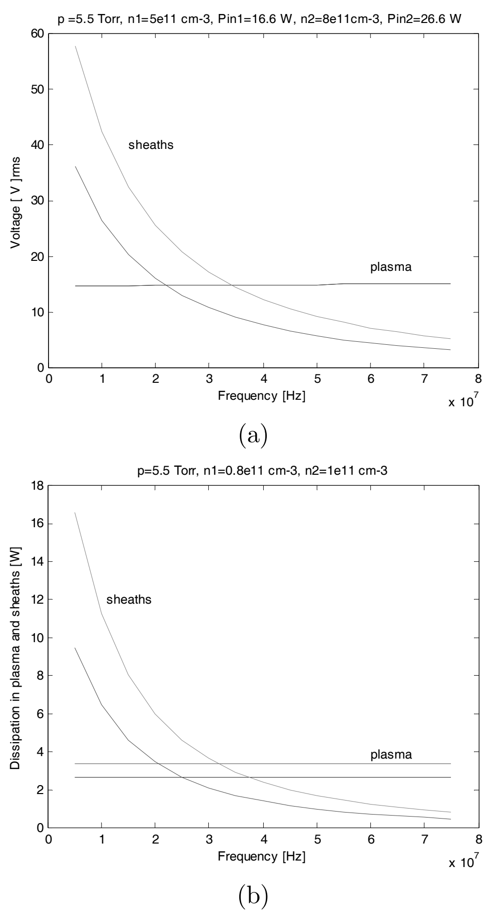
Torr mm, and at λ = 3.39 μm we have He:Ne ≈ 7:1 for pD of about 8.5 Torr mm.

Although we did not find any optimized trial or research on an fD invariant of rf excited He-Ne lasers (in the range of frequency for CO_2 lasers), the present knowledge about rf discharge means that we can confidently approximate the frequency value for our lasers.

At first, the selection of the tube diameter is the most important parameter when looking to apply the laser for remote methane detection. It is related to the expected transmitter-receiver optics of the system. To have a strong and durable laser transmitter, with a four channel construction, we decided to use an active medium of diameter 2.8 mm and length 50 cm. Using the dependence $pD \approx 8.5$ Torr mm we can then fix the pressure at 8.5/2.8 ≈ 3 Torr.

In the past few decades, the low-temperature rf plasmas are being utilized in an increasing number of applications from materials processing, to lighting to lasers. Through experimental and theoretical studies, significant progress in understanding many effects on discharge properties has been achieved. There are several different approaches that can be taken in modeling rf discharges. One uses either a fluid treatment, capacitively coupled discharges (CCD), a kinetic scheme, or a hybrid combining aspects of the fluid and kinetic schemes. A variety of diagnostic techniques have been applied to measure parameters in discharge systems as well [17]. One very important parameter to describe plasma characteristics is the ω/ν value, were $\omega = 2\pi f$ and ν is the electron collision frequency to neutral species. For helium the value $\nu \approx 2.4\times10^9$ p[Torr] s^{-1} (at electron energy ε > 4 eV), and for p = 3 Torr we have $\nu \approx$ 7.2 GHz and inequality $\nu >> \omega$ because we do not assume the work in the microwave band. For this case, in the simplest CCD model, we can then assume that the electric system may be considered as a series of sheath capacitances (lossless) and a plasma resistance. The discharge consists of two regions, a time invariant quasi-neutral plasma region where $n_e = n_+$, and the rf sheaths, where n_e is time varying electron density while n_+ is time invariant. In other words, in this simple model ion density n_+ is assumed to be constant in the discharge volume, and the electron gas of density ne as a whole oscillates around middle point with the same amplitude d_{As}. For this one-dimensional model the discharge voltage ($V = V_a\, exp(i\omega t)$) on electrodes is given by the sum of voltages across the electrode sheaths V_S and the plasma voltage V_P, shifted in phase by approximately $\pi/2$. Therefore [14]: $V_a = (V_{aS}^2 + V_{aP}^2)^{1/2}$, where $V_{aS} \approx 2en_e d_{As}^2/\epsilon_0$, $V_{aP} = E_a(D - 2d_{As})$, and e is the elementary charge, ε_0 is the vacuum permittivity, E_a is the amplitude of the field in plasma. The simulation results are shown in Fig. 2a.

Generally, there are two ways to consume the rf discharge power in a capacitive discharge. One is power dissipation conducted by ions in sheaths (P_{sh}), the other is a power dissipation conducted by electrons in a bulk plasma (P_p). For lasers the latter way is more convenient and also the α-mode is the most favorable form of the rf discharge. The total discharge power can be expressed as follows: $P_t = P_p + P_{sh} = V_{pr}I + R_{sh}I^2$, where I is the rf discharge current in rms, V_{pr} is an ohmic component of the rf voltage across the bulk plasma in rms that includes collisional and stochastic electron heating, and R_{sh} is the sheath resistance. For good laser behavior we have to strive for $V_{pr}I >> R_{sh}I^2$, even for a large current. Since V_{pr} is almost independent of current and driving frequency, it means that R_{sh} must be as small as possible. The expression for R_{sh} derived under collisional sheath regime by Beneking [18] shows that it depends only on external parameters: $R_{sh} \propto k\, A_{sh}^{-1.5}\, p^{-0.5}\, I^{0.5}\, \omega^{-2.5}$, where A_{sh} is sheath area, and k is a mobility constant. Also experimentally it was found over a wide range of discharge conditions that $R_{sh} \sim (I/p)^{0.5}$ (in He, p = 0.03-3 Torr, f = 13.56 MHz) [19]. So in the case of lasers, to decrease R_{sh} we should choose the highest possible frequency. Voltages and dissipation power for sheaths and plasma based on



(a)

(b)

FIG. 2. Frequency dependencies of some α-mode rf discharge parameters for helium: (a) the simple CCD model, (b) power dissipation in sheaths and plasma.

relationships discussed above are shown in Fig. 2 a, b. The limits for used frequencies, at typical values of p and D determined above, can now be estimated.

From the point of view of laser optimization not only is the α-mode of discharge important, but also the size of the bulk plasma where the passing of energy to the active medium and excitation of the upper laser level takes place. To have sufficient space for a plasma, which serves as the active medium, the size of the gap D must be quite large as compared to the sheaths thickness $d_{sh} \approx d_{As} \approx v_d/\omega << D$, where v_d is an electron drift velocity corresponding to the plasma field amplitude E_a, and therefore $\omega >> v_d/w$. For example, if $v_d \approx 10^6$ cm s^{-1} and D = 2.8 mm, frequency $f >> 1$ MHz is necessary.

Fig. 2 illustrates three important issues related to the frequency limits of rf discharge: two of them restricting low-frequency operation and the third indicating an upper frequency limit. At lower excitation frequency the sheaths voltage can becomes large enough and creates a risk of α-γ transition. Then for the sheath voltage comparable with the α-γ transition sheath voltage (V_t) we have the lower frequency limit (for unballasted metal electrode). For our laser, from Fig. 2 one can conclude that the value of 5-10 MHz is acceptable and that it depends on the discharge current.

The theoretical model and some experimental results concerning rf discharge in the α and γ regimes for the frequency band of f = 1-10 MHz in helium gas at moderate pressures and pD = 1-40 Torr cm were investigated by Godyak and Khanneh [20]. They showed that the current/voltage characteristics of rf discharges (j/p and j/f) in α-mode behave as invariants (similarly to the case of the CO_2 laser), and that α-mode exists for $f/p >$ 2-10 MHz/Torr at their experimental conditions. In other words, transition voltage V_t increases with increasing pressure and decreasing frequency. As we take $p \approx 3$ Torr for our laser, for frequency it will be $f >$ 6-30 MHz. A consideration of power losses in the sheaths due to the ion sheath ohmic resistance gives another limit (Fig. 2b): the ratio of the power dissipation in the sheaths to the plasma power dissipation should be lower than about 10%, therefore $f > 60$ MHz.

The high frequency limit results from the decreased sheath impedance at increased f. Above the point where the values of sheaths and plasma voltages are comparable, the slope of the discharge current-voltage characteristics is only slightly positive and there is a risk of discharge instabilities (first of all for naked electrodes). In the case of covered electrodes this limit can be significantly increased. In our construction of "coated electrodes", the total capacitance of nonconducting space charge region and dielectrics per unit area will be defined by $\varepsilon_0 / (d_{sh} + d_d / \varepsilon_r)$, where ε_0, ε_r are the vacuum and relative dielectric permittivity ($\varepsilon_r = \varepsilon / \varepsilon_0$), and d_d is dielectric thickness. For our Pyrex tube the upper limit is shifted considerably above 100 MHz and, on the basis discussed above, we have decided to use a supply frequency of f = 81.36 MHz for the experiments.

In our constructions the discharge takes place inside the glass tubes and the tube walls form a distributed reactive ballast resistance to the plasma. Fig. 3a shows an equivalent circuit of the head of one channel, where the total capacity of the head C_h is connected in parallel with loss resistance R_h and shunt inductors L_{sh}. When the laser is running, the equivalent circuit of the head takes a form presented in Fig. 3a for one channel and a form showed in Fig. 3b for four tubes. A plasma resistance R_p and a sheath capacity C_{sh} are included in the equivalent circuit as impedance Z, and plasma capacity C_p is neglected.

III. Experimental results

The main objective of the experiments was to investigate the steady-state characteristics of an rf discharge pumped He-Ne-gas laser and the feasibility of cw operation for a single channel. As stated above, the four channel construction is filled from a common container, and we have the same voltage supply for each tube in this system (Fig. 3b). It is easier to carry out the optimization research with one tube, and such results will be shown.

The discharge tube was 55 cm long and the inner diameter of 2.8 mm with CaF_2 Brewster angle windows (although internal mirrors were also used on occasion). The electrodes of width 5 mm and 50 cm in length were situated along the axis of the discharge tube and were separated from the gas plasma by dielectric walls of this tube. The optical cavity had a 50 cm gain length and a 65 cm mirror separation. Resonator consisted of a 2 m concave reflector (R = 99.9% at 3.39 μm) and a flat partial reflector with a 3.39 μm antireflection coating on the rear surface. The mirrors were coated with narrowband dielectric coatings on BK7 and CaF_2 substrates. The optics were optimized for 3.39 μm.

The preliminary experimental results are showed in Fig. 4-6 and described briefly as follows. The dependence of the laser output power on the supply power laser was measured with different values of the filled-gas pressure

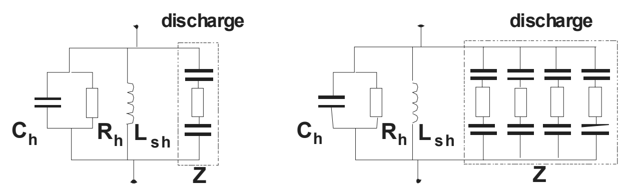


FIG. 3. Equivalent schemes of the transverse rf capacitive α-discharge for: (a) one channel laser, (b) matrix structure.

and the gas-mixing ratio, as shown in Fig. 4, 5.

As we can see in Fig. 4, the reduction of pressure gives an increase of output power. By decreasing pressure we come close to the optimum p ≈ 3 Torr, and therefore the output power is gradually growing. But diminishing the pressure simultaneously causes the increasing of breakdown voltage V_B, which for our laser (the left hand branch Paschen's curve, $pD \approx 15$ Torr mm) grows from V_B(6 Torr) ≈ 75 V to 135 V_B(3 Torr) [14]. That is why the ignition of the mixture was more and more difficult. Moreover, with lower pressure and higher input power, the phenomenon of discharge "flowing out" appeared (towards direction of Brewster windows). From these two factors we can conclude that the pressure p = 5.5 Torr is optimal for our construction.

After filling the laser to the pressure that was recognized as optimum, we varied the composition of mixture by a wide range (Fig. 5). For a given power of the generator we obtained a distinct optimum for the mixture ratio of He:Ne = 13:1. Such behavior of an rf excited laser is similar to that of a dc current supply. Experimentally and theoretically it was shown that increasing the pD parameter requires an increase in He in mixture, eg., for $pD \approx 3.5$ Torr mm, He:Ne = 5:1, and if $pD \approx 5$ Torr mm, He:Ne = 10:1 (at λ = 638 nm) [21]. A small amount of neon means a small concentration of excited atoms on the upper laser level and a small output power. Increasing the quantity of Ne in the mixture (for a fixed pressure p and power P_g) allows us to achieve the maximum, but a further increase of Ne gives a drop of the output power. It means that the decreasing of the He:Ne ratio simultaneously decreases the value of He through which the upper laser level is pumped. In other words, the optimum He:Ne pressure ratio is related to a optimum of the average electron energy in the plasma.

To calculate the small signal gain g_o and the saturation intensity I_s, the laser power was measured as a function of output mirror reflectivity for a given gas mixture and pump power density. The output mirror reflectivity was varied from 28% to 83% (Fig. 6 a, b). The dependence of g_o, and I_s on pump power density, Ne concentration, and total gas pressure was investigated. The g_o, I_s were determined from the data by performing a nonlinear fit to formula for the mixed broadening. In our lasers the parameter $\rho = \Delta\nu_h^2 \ln 2 / \Delta\nu_D^2 \approx 0.12$, where $\Delta\nu_h$ is the full width at half-maximum of the unsaturated Lorentzian, $\Delta\nu_D$ is the full Doppler width at half-maximum, and output power can be describe by function [22]:

$$P_{out} = 0.5\, S_b\, T_m\, I_S\, (0.022 r^2 + 0.978 r - 1) \qquad (1)$$

where r is a threshold coefficient representing the ratio of round-trip gain to loss, T_m is the transmission of the flat output coupler, and S_b is the area of the beam. Representative fits are shown in Fig. 7 a, b. The uncertainties of ~ 10% in small signal gain, ~ 10% in saturation flux, and ~ 100% in non-saturable loss were determined. The uncertainty in the loss was large because its absolute value was very small (< 0.01). We estimated the typical values of $I_s \approx$ 3-4 W/m^2, and $g_0 \approx$ 1-2 cm^{-1} for our lasers.

The preliminary experiments with matrix construction gave the results as we expected. The input power was

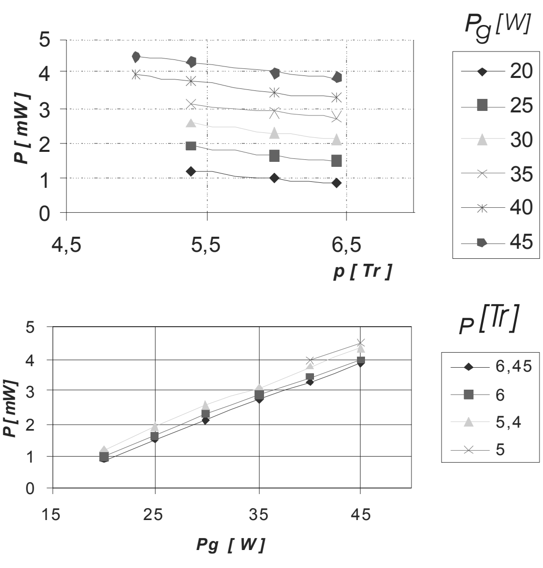


FIG. 4. Dependence of the output power versus the pressure of mixture for different levels of power supply; T_M=46%, He:Ne=15.4:1.

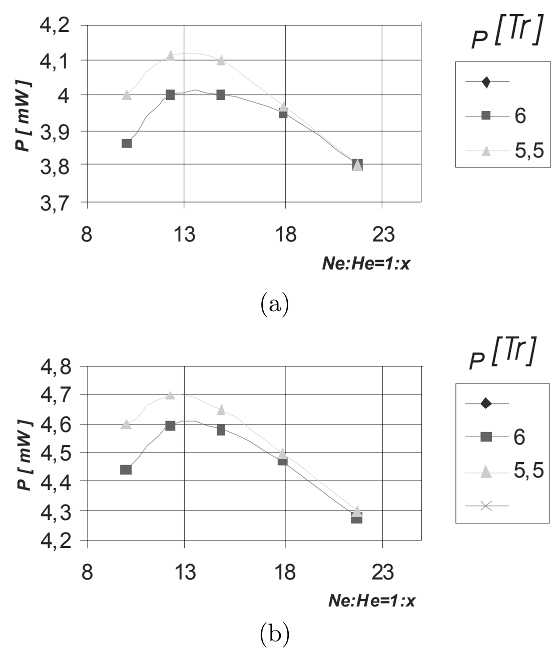
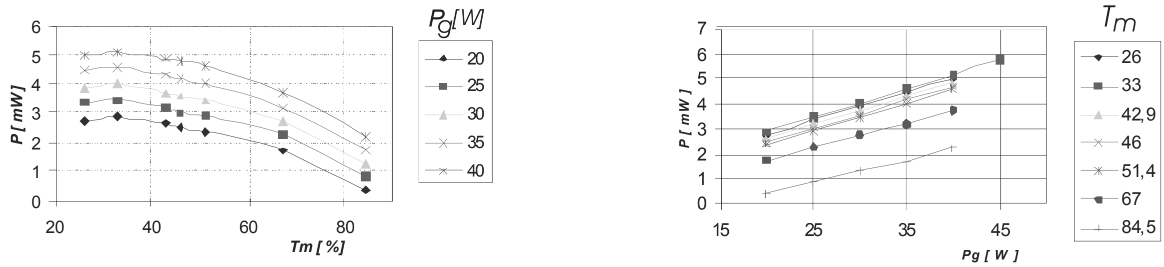
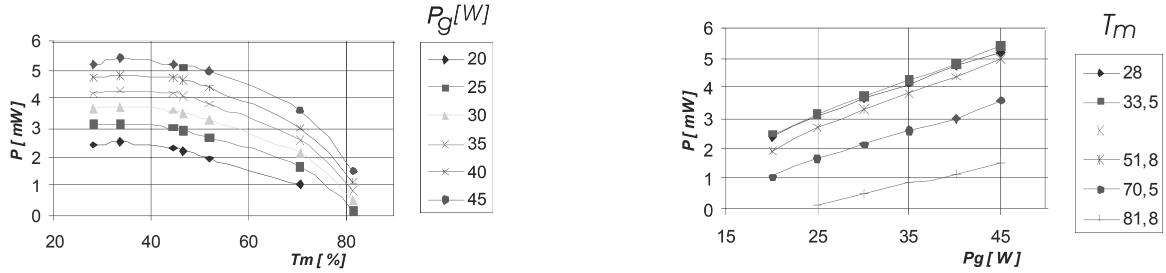


FIG. 5. Dependence of the output power versus the mixture-ratio for different levels of power supply: (a) T_M=33%, P_g=30 W, (b) T_M=33%, P_g=35 W.

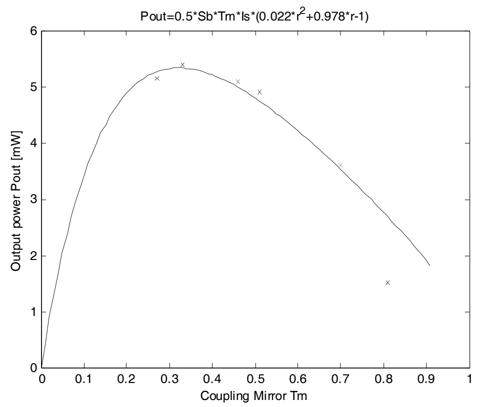


(a)

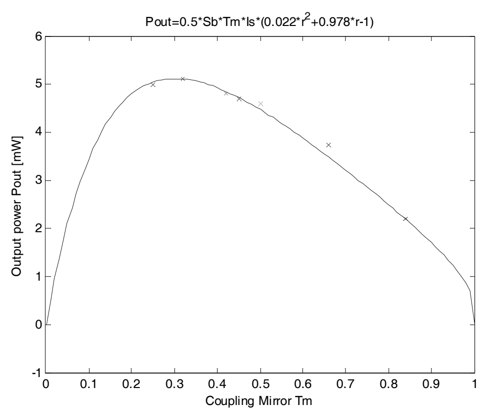


(b)

FIG. 6. Experimental laser output shown as a function of mirror transmission for different levels of the generator power: (a) total pressure p_M=5.5 Tr, mixing ratio He:Ne=18:1; (b) p_M=6.5 Tr, He:Ne=10:1.



(a)



(b)

FIG. 7. The calculated optimum laser output is shown as a function of mirror transmission for different gas ratio and pressure: (a) p_M=6.5 Tr, He:Ne=10:1, (b) p_M=5.5 Tr, He:Ne=18:1. (for the data from Fig. 6 a, b)

multiplied by four. Experiments were carried out with one common and flat output mirror ($T_m \approx 35\%$) and four independent 2 m concave reflectors. We obtained more than 20 mW under optimized conditions for a single laser tube (Fig. 8).

In the case of a one channel laser, the demonstrated results are comparable with laser parameters offered on the market, the ratio P_{out}/L is similar (about 10 mW/m). But the solution with rf discharge appears to be simpler and to have also increased longevity. The four channel construction improves results considerably. In the case of some applications, e.g. the remote detection of methane, this design facilitates practical implementation in the near future. We have the radiation source which is simple and compact, with the ratio P_{out}/L above 40 mW/m. It is worth underlining that the optimization of frequency was not conducted, and its influence can be substantial.

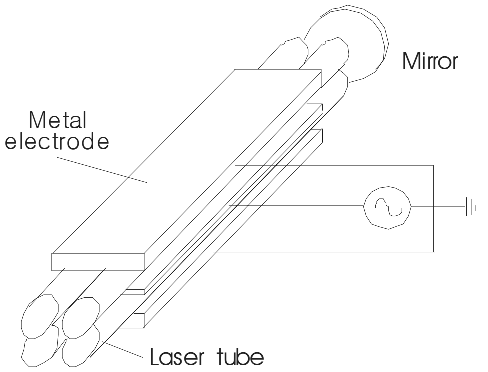


FIG. 8. Sketch of geometry and electrode configuration of matrix laser.

In recent years, a variety of diagnostic techniques and computer simulations have been improved, and low-temperature rf plasmas applications are increased [17]. Optimizations of the plasma properties to specific tasks are underway. It gives hope that processes occurring in plasma and electrode sheaths of lasers can be better understood and explained.

Generally, for both dc and rf discharges, the invariancy of the parameters *E/p* and *pD* defines the optimum laser excitation conditions (optimal average electron temperature or average electron energy). But for rf discharges we can, through the change of frequency, change the parameters of sheaths and bulk plasma. For example, according to theoretical works [23, 24], the effects of ω/ν on the electron energy distribution function (EEDF) in plasma are as follows with increasing ω/ν: a) the EEDF tends to move towards a Maxwellian distribution, b) population of electrons in the high-energy tail of the EEDF increases, c) the average electron energy decreases, and d) the total electron density increases at a constant power density.

Some excess of high-energy electrons seen in helium rf discharges at relatively high pressures of 1-5 Torr may result from the collisional overheating in the vicinity of the plasma boundaries as well as from superelastic collisions of thermal electrons with metastable excited helium atoms and Penning ionization processes with participation of two excited helium atoms. These phenomena change the balance of production and loss of electrons in the gas mixture, and are important for the creation of population differences of laser transition (the electron-neutral collision processes that need energetic electrons such as excitation or molecular dissociation can be intensified at higher driving frequencies, even if the total electron density decreases.) [25, 26].

IV. CONCLUSIONS

Steady-state lasing for 3.39 μm has been achieved both in the single rf pumped He-Ne laser and in the four channel structure. The results suggest that efficient, cw operation would be possible for matrix construction. The technological parameters and reliability of the system elements are acceptable. The fragile elements (glass tubes) are surrounded by grounded metal electrodes. The simple construction of a laser with one channel and rf supply gave a value of P_{out}/L comparable with that seen on the market with dc excitation, however, we obtained higher P_{out}/L values for the four channel system.

Improved parameters can be expected after the optimization of frequency. Further studies on the pulse regime are also planned for single and matrix lasers.

ACKNOWLEDGMENTS

This work has been supported by Brain Pool of The Korean Federation of Science and Technology Societies, and RIC program of Dankook University Medical Laser Center.

*Corresponding author: woon@honam.ac.kr

REFERENCES

[1] O. Svelto and D. C. Hanna, *Principles of Lasers*, Plenum Press, 1998.
[2] Y. Ling, M. Qian, and P. Lu, Rev. Sci. Instrum. 66, 4055-4058, 1995.
[3] www.jodon.com., www.neoark.co.jp.
[4] Y. Ling, J. Phys. D: Appl. Phys., 39, 1781-1785, 2006.
[5] Y. Li, M. Chen, Z. Li, J. Liu, J. Guo, and Y. Yang, Appl. Opt., 46, 591-601, 2007.
[6] Muller Ya. N., Radiotechnika, 22 (106), 55-68, 1979.
[7] Muller Ya. N., Geller V. M., Khrustalev V. A., Sov. J. Q. E., 9 (10), 1302-1303, 1979.
[8] Geller V. M., Grif G. I., Khrustalev V. A., Avtometria, N1, 35-45, 1984.
[9] Andrews D. A. and King T. A., J. Phys. D: Appl. Phys., 22, 1315-1320, 1989.
[10] Andrews D. A. and King T. A., J. Phys. D: Appl. Phys., 22, 1308-1314, 1989.
[11] Glebov D., Stepanov V., Demin A., Yastrebkov A., New powerful coaxial He-Ne laser with cw and RF pumping, Gas discharges and their applications, 457-460, 1997.
[12] M. Kopica, J. W. Choi, Proceedings of SPIE, vol. 5154, 146-152, 2003.
[13] M. Kopica, J. W. Choi, Proceedings of SPIE, vol. 5120, 106-108, 2003.
[14] Reizer Yu P., Shneider M. N., Yatsenko N. A., *Radio-Frequency capacitive discharges*, CRC Press, 1995.
[15] M. Kopica, M. Strzelec, Z. Trzesowski, Biuletyn WAT, 9, 55-71, 1993.
[16] P. P. Vitruk, H. J. Baker, and D. R. Hall, IEEE JQE, vol. 30, no. 7, 1623-1634, 1994.
[17] M. A. Lieberman, A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, John Wiley & Sons, 2005.
[18] C. Beneking, J. Appl. Phys. 68, 4461-4473, 1990.
[19] V. A. Godyak, R. B. Piejak, Plasma Science, IEEE Conf., Abstracts.,171, 1991.
[20] V. A. Godyak and A. S. Khanneh, IEEE TPS, vol. PS-14, 112-123, 1986.
[21] C. S. Willett, *Introduction to Gas Laser: Population Inversion Mechanisms*, Oxford: Pergamon, 1974.
[22] L. W. Casperson, Appl. Opt., 19, 422-434, 1980.
[23] L. L. Alves and C. M. Ferreira, J. Phys. D: Appl. Phys. 24, 581-592, 1991.
[24] C. M. Ferreira and J. Loureiro, J. Phys. D: Appl. Phys. 16, 2471, 1983.
[25] V. A. Godyak, R. B. Piejak, and B. M. Alexandrovich, Plasma Sources Sci. Technol. 1, 36-58, 1992.
[26] S. K. Ahn, S. J. You, and H. Y. Chang, Appl. Phys. Lett., 89, 161506, 2006.