New trend in the technology of cw RF-excited sealed CO_2 waveguide lasers

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ABSTRACT

An investigation and optimisation of a single channel transverse RF excited CW sealed CO_2 waveguide laser is presented. The laser performance has been studied as a function of various parameters like the excitation frequency, gas pressure, gas mixture composition, and cooling temperature for two pairs of metal electrodes with equivalent sizes, but made of different material - gold plated copper and aluminium. The waveguide structure used was metal-ceramic with an active discharge volume of 2.5x2.5x370 mm^3. Single-pass small-signal gain measurements for the two sets of electrodes have been performed, as well.

The experiments show that the influence of the electrode material on the laser behaviour is significant, while it was generally accepted as a factor of no importance. The best result we obtained with the Al electrodes was a specific output power of 0.78 W/cm with an efficiency of 11% at 125 MHz excitation frequency and 140 Torr of 1:1:5+5% (CO_2:N_2:He+Xe) gas mixture, which is very close to the highest specific power of 0.85 W/cm, previously reported. With the gold plated electrodes a specific output power of 1.1 W/cm with an efficiency of about 13 % was achieved at 190 MHz and 100 Torr 1:1:5+5% gas mixture. This improvement is most likely related to the catalytic properties of the gold layers. This favourable process is accelerated at elevated temperatures, so that an intensive cooling is not necessary for good laser performance. The gain measurements confirmed this behaviour. With gold plated electrodes at certain experimental conditions an increase of the gain of a factor 2 was observed.

1. INTRODUCTION

In recent years there has been seen a considerable increase in the popularity of the CO_2 waveguide lasers, in particular with transverse RF excitation[1], because of their numerous inherent advantages over the conventional lasers with dc gas excitation. RF-excited CO_2 waveguide lasers offer a dramatic decrease in overall size, higher pressure and lower drive voltages operation, longer lifetimes, higher gain and an output power of more than 1W/cm of discharge length[2]. However, despite of the advantages which the RF-excited waveguide lasers have, there are a few limitations for the output power of the CO_2 gain medium. First, the input power is limited by the need to keep the gas temperature below a certain level, typically 600K, above which the population inversion drastically decreases. Therefore, an enhanced cooling is strongly required and wide-spread in use to improve the laser efficiency. A second process, which inevitably occurs in an electrical discharge and reduces significantly the laser gain[3-5] and output power[6, 7], is the dissociation of CO_2 molecules. Due to the electron impact severe decomposition reactions of the initial CO_2:N_2:He+Xe gas mixture take place:

$$CO_2 + e \rightarrow CO + O + e, \quad (1)$$
$$CO_2 + e \rightarrow CO + O^{-}. \quad (2)$$

Both the depletion of the CO_2 density and the build up of CO, O_2 and/or O^- have a poisoning effect on the laser performance, because of the reduction of the energy transfer rate for CO_2 excitation from vibrationally excited N_2 and CO on one side and the adversely affected electron energy distribution on the other side. However, the process of dissociation is not unlimited. At the same time recombination of CO and oxygen occurs in the volume of the discharge and on the surface of the electrodes. So, in a sealed-off CO_2 laser the dissociation of CO_2 proceeds until an equilibrium is reached. There are many factors influencing the equilibrium level of dissociation as for example the gas pressure and mixture composition, RF power density, electrode material, etc. In a CO_2 RF-excited waveguide laser, typically about 50-70% of the CO_2 is dissociated at equilibrium[8-10].

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These undesirable effects of decomposition can be overcome by incorporating a CO oxidation catalyst into the laser system which converts the dissociated products back into CO_2. Due to the specific configuration of transverse RF-excited waveguide lasers, where the internal electrodes are in contact with the active medium along the entire discharge length, a catalytically active electrode surface[9, 11] is a very suitable solution.

An catalyst which must be active under CO_2 laser discharge conditions and incorporated on the electrodes of the waveguide, meets many requirements. It must operate under ambient laser temperatures and low O_2 concentrations. Additionally, the reflectivity and smoothness of the catalytic surface should be high to keep the optical losses low. Such a candidate catalyst is gold[2, 9, 10, 12]. Although Macken et al.[10] claimed that Au is an ambient temperature catalyst, in general higher temperatures increase the catalytic activity that is in strong contradiction with the requirement for low coolant temperature in order to improve the laser efficiency. Hence, it is of great interest to find the optimum coolant temperature which benefits both the catalytic activity and laser excitation and at which the highest gain and laser output power can be obtained.

This paper reports on an optimised single-channel CW transverse RF-excited sealed CO_2 waveguide laser with gold plated electrodes that generates 42W at an efficiency of 13% in 1:1:5+5% (CO_2:N_2:He+Xe) gas mixture. This high output power is attributed to the choice of the proper temperature providing optimum conditions for the laser operation. Measurements of the laser output power and small-signal gain show an significant enhancement effect with time at which the temperature of the upper electrode is increased. Similar measurements have been performed with an equivalent pair of aluminium electrodes, but the above mentioned enhancement effects were not observed. Analysing the results presented here and the results of some preliminary measurements with a mass spectrometer the conclusion is made that the remarkable improvement of the laser gain and output power can be related to the increased catalytic activity of the gold plated electrode surface at elevated temperatures.

2. LASER DESIGN AND CONSTRUCTION

The design of the laser, shown in section along two perpendicular axes in Fig. 1, was based on a metal/ceramic sandwich waveguide structure with internal dimensions of 2.5 x 2.5 x 370 mm^3. The discharge channel is placed into a silver plated copper housing, which acts as the vacuum envelope or gas reservoir. In the laser housing the ratio of the total gas volume to the volume of the active region was 1730 : 1. Both electrodes were provided with an copper heat sink and were spaced by polished alumina ceramic sidewalls. In order to reduce the electrical losses in the dielectric the sidewalls were of height 20 mm and thickness 4 mm. The sidewalls were tightened to the electrodes with aluminium clamps at the ends of the waveguide.

In our experiments two different electrode materials were used, namely aluminium and gold plated copper. The surfaces of all electrode pairs were polished with a diamond grinding wheel. Then, for the copper electrodes, a gold film was evaporated on an intermediate film of niobium. In all cases the roughness of the electrode surface was less than 0.2 μm

Optics were mounted 3-4 mm on removable brass flanges sealed with Viton O-rings from the ends of the waveguide, to avoid damages caused by the discharge. The laser resonator was formed by a coated silicon total reflector (99.8 %) and an outcoupling ZnSe mirror of 91.3% reflectivity. Both mirrors were flat. An independent 1-inch-diameter anti-reflection coated ZnSe window, sealed with an Viton O-ring, on the optical flange of the outcoupling mirror, was used to provide the vacuum seal. Optical alignment was achieved using standard kinematic-type mirror holders with precise adjustable positioning about two axes.

The waveguide laser utilises a parallel-resonant distributed-inductance technique[13] to uniformly distribute the voltage along the electrodes and hence to uniformly excite the gain medium. With this method 6 equal-value parallel inductors, uniformly spaced from the center of the laser channel, approximate a distributed inductance and form a parallel resonance with the high capacitance structure of the waveguide, mainly formed by the ceramic sidewalls. Five different sets of inductors were prepared and their values were chosen to resonate with the discharge structure at five drive frequencies of between 85 and 200 MHz. The laser was powered by a broad band (10 kHz-220 MHz) variable output RF

amplifier with a maximum output power of 500 W. A single RF feed at the center of the top electrode supplies energy to the cavity through a two-component matching circuit.

3. EXPERIMENTAL CONDITIONS AND MEASURING METHODS

A schematic diagram of the overall experimental system, including the small-signal gain set-up is shown in Fig. 2. In laser output power measurements the anti-reflection windows at the ends of the waveguide channel were replaced with the above mentioned resonator mirrors.

A two-stage pumping system evacuated the waveguide cavity to about 10^{-6} Torr. Premixed research grade gases backfilled the laser at total pressures of between 40 and 140 Torr. Gas mixtures with 1 volume part CO_2, 1 volume part N_2 and 3-8 volume parts He were used.

The RF power was measured with a Bird RF power meter (model 4421) through a Bird bi-directional power sensor (model 4022). The input power was calculated to be the difference between the forward and reflected powers. The laser output power was measured with Coherent model 201 power meter.

Single-pass small-signal gain measurements were performed using a conventional dc-excited CO_2 probe laser. The laser was frequency stabilised with a Lansing model 80.215 lock-in stabilizer and operated on the 10P(20) line at about 2 W. The single pass gain α_0 was calculated as $\alpha_0=1/L\cdot\ln(P_1/P_0)$, where P_1 and P_0 are the transmitted probe laser powers through the waveguide with and without waveguide discharge, respectively and L is the discharge length.

The electrodes could be cooled by tap water or by a cooling system (MGW Lauda, type TUK 30D), operating with ethylene glycol at temperatures of between -30°C and 100°C. In the experiments where only the ground electrode was cooled, the temperature of the top electrode was measured with a conventional alcohol thermometer placed at the bottom of the heat sink. Dow Corning heat sink compound was used to provide good thermal contact between the heat sink surface and the thermometer. The difference between the temperature of the measuring point and the electrode surface is calculated to be less than 11°C. Due to the construction and the dimensions of the ceramic sidewalls a large thermal impedance is expected in the cooling by conduction of the top electrode. Unless otherwise indicated, the initial temperature of the non-cooled top electrode was about 20°C, but with discharge "on" it reached different steady-state temperatures, depending on the input RF power.

4. RESULTS AND DISCUSSIONS

A parametric study has been performed with both the aluminium and gold plated copper electrodes at different excitation frequencies, gas pressures, mixture compositions and for a variety of cooling regimes and reflectivities of the outcoupling mirror in order to find the optimum conditions for laser operation. The optimum cooling regime was achieved with a non-cooled top electrode and tap water cooled ground electrode. As a result with the Au-plated electrodes an output power of 42 W was obtained at a drive frequency of 190 MHz, 91.3 % mirror reflectivity and at 100 Torr of 1:1:5+5 % (CO_2:N_2:He+Xe) gas mixture. The efficiency at the peak output power was about 13 %. This is the highest output power reported up to now from a single channel waveguide laser.

In the same thermo regime the output with the Al electrodes was optimised and resulted in a maximum output power of 29 W with an efficiency of 11 % at 125 MHz excitation frequency and 140 Torr of 1:1:5+5 % gas composition. The optimum outcoupling was the same as in the case of the Au-plated electrodes. The specific output power of 0.78 W/cm, obtained with the Al electrodes is actually very close to the highest specific power of 0.85 W/cm, previously reported also with Al electrodes, whilst with the Au-plated electrodes an improvement of 33 % is obtained.

It is seen that even in a high temperature regime the output power can be increased by choosing a proper electrode material. To investigate the influence of the temperature on the laser performance, for both electrode materials the small-signal gain and the laser output power were measured versus operational time during which the temperature of the top electrode was increasing. Unless otherwise indicated, the excitation frequency was 190 MHz.

Measurements of the small-signal gain for both pairs of electrodes at total pressures of between 40 and 140 Torr were performed using a mixture 1:1:5+5% (CO_2:N_2:He+Xe). The time variation in α_0 for the experiments at 40 and 60 Torr at RF input power of 90 and 200 W, respectively is shown in fig. 3. It is seen that the gain with the Au-plated electrodes is much higher even when the discharge is just turned on. Then it increased markedly (about factor of 2) with time while heating-up of the non-cooled electrode also occurred. The system reached an equilibrium temperature roughly 80 minutes after switching on. In the same period of time the gain reached the highest value. In contrast, the experiments with the Al electrodes showed that α_0 slowly decreases with warming-up time. For both of the electrode materials the gain was found to be inversely proportional to the gas pressure.

In fig. 4 the laser output power behaviour versus time is plotted at 40, 60 and 100 Torr total gas pressure of the above mentioned mixture and RF input powers of 120, 200 and 300 W respectively, for the two electrode materials. Also, the temperature of the upper Au-plated electrode is indicated at about 30, 60 and 90 minutes after the discharge is switched on. The temperature of the upper Al electrode is not given, since at each gas pressure examined the RF input powers for the both electrode materials were the same and only a few degrees difference in the temperature appeared. It is to be seen that again the Au-plated electrodes cause an increasing output with respect to warming up time, in contrast to the Al electrodes. These observations for the Au-plated electrodes are very remarkable, because the CO_2 laser mechanism in the system predicts a diminishing output effect for increasing system temperatures[3], as was observed for the Al electrodes.

The enhancement effects of Au-plated electrodes compared to Al ones have also been investigated for a 1:1:3+5% gas mixture. Again with the increase of temperature a rise of gain (fig. 5) and laser power (fig. 6) was observed, although less pronounced. A similar behaviour is found for this gas mixture at 125 MHz excitation frequency (not illustrated). The lower enhancement effect with temperature for 1:1:3+5% gas mixture is connected with the fact that in gas mixtures with lower He partial pressures, the gas temperature is higher and consequently worse conditions for the population inversion are available. Additionally, the fractional dissociation of CO_2 is lower and a lower enhancement should be expected.

It should be noticed that in all experiments with Au-plated electrodes the gain and the output power started to increase after a typical time of 30-40 minutes. This time period coincides with the rise of electrode temperature above 40-50^{o}C. It is most likely that the observed phenomena with the Au-plated electrodes are due to an improved catalytic activity at elevated temperatures.

In order to prove this hypothesis some additional experiments have been carried out in a variety of cooling regimes. The first experiment is performed at low RF input power of 128 W, 180 MHz and 60 Torr of 1:1:8+5% gas mixture. These gas mixture and low input power level were chosen in order to minimise the warming up effects of the upper electrode and hence to attain an effective and homogeneously distributed cooling of both electrodes. The ground electrode was cooled with the ethylene glycol cooling system, while the top electrode was not cooled. Fig. 7 shows the laser output power behaviour with time in two different cooling regimes. During the first 75 minutes the lower electrode was kept at a temperature of 0^{o}C. It was observed that in this period of time the output power remains constant at 17 W. Then, without switching off the laser, the cooling system was adjusted to 24^{o}C. During the following 45 minutes the temperature of the coolant and consequently the electrodes reached this temperature and the laser output power markedly increased up to 23 W.

To investigate further the effect of cooling, experiments were conducted with two cooled electrodes. Fig. 8 shows the laser output power behaviour with time when both electrodes were kept at 10^{o}C. The results are plotted for 80 and 100 Torr of 1:1:8+5% gas mixture at input RF power of 250 and 340 W, respectively. The excitation frequency was 190 MHz. The output power almost did not change with time and was of about 23 and 24-19 W at 80 and 100 Torr, respectively. Under the same experimental conditions, except that the ground electrode was water cooled and the top electrode non-cooled, an output power of 31 and 37 W at 80 and 100 Torr, respectively was obtained.

Some initial experiments with a mass-spectrometer have confirmed the hypothesis that the increased gain and output power at high electrode temperatures can be attributed to the much stronger catalytic activity of gold than that of aluminium[9] (if any) on the dissociation processes. Contrary to our results W. Haas et al.[9] presented Al as an electrode surface material superior to gold in recombinational ability. The disagreement with this report can be attributed to the

differences in the experimental conditions. For their investigations, the surface temperature of the waveguide was less than 25°C, whereas one of our electrodes reaches equilibrium temperatures between 35 to 80°C, depending on the input RF power. Also in their experiments the gold plated electrodes were prepared by sputtering gold directly on an Al surface, while our gold layers were evaporated on copper with an intermediate layer of Nb. The role of Nb has not yet been studied. Experiments recently performed with a so called noble-metal-reducible-oxide[14] catalyst consisting of Au/MnO_2, show similar behaviour and an increased activity is also found at higher temperatures. Whether the same mechanism holds for our surface catalyst is at the moment not known.

In summary a significant improvement of the performance of a compact sealed-off RF-excited CO_2 waveguide laser with warm gold plated electrodes has been achieved. Experiments have been performed to prove that this enhancement effect is due to an increased catalytic activity of the gold plated electrodes at high electrode temperatures.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. D. R. Hall and C. A. Hill, Handbook of Molecular Lasers, edited by P. K. Cheo (Marcel Dekker, New York, 1987), ch. 3.
2. M. B. Heeman-Ilieva, Yu. B. Udalov, W. J. Witteman, P. J. M. Peters, K. Hoen, and V. N. Ochkin, "rf excited 1.1W/cm wavequide CO_2 laser", J. Appl. Phys. **74**, 4786 (1993).
3. W. J. Witteman, The CO_2 laser, Springer Ser. Opt. Sci. **53**, Springer, Berlin (1987).
4. K. J. Siemsen, "Axial gain distribution in a cw CO_2 laser", Appl. Opt. **19**, 818 (1980).
5. K. J. Siemsen, J. Reid, and C. Dang, "New Techniques for Determining Vibrational Temperatures, Dissociation, and Gain Limitations in CW CO_2 Lasers", IEEE J. Quantum Electron. **QE-16**, 668 (1980).
6. A. L. S. Smith, T. H. Bett, and P. G. Browne, "The Effect of Gas Additives on TEA CO_2 Lasers", IEEE J. Quantum Electron. **QE-11**, 335 (1975).
7. P. Bletzinger, D. A. LaBorde, W. F. Bailey, W. H. Long Jr., P. D. Tannen, and A. Garscadden, "Influence of Contaminants on the CO_2 Electric-Discharge Laser", IEEE J.Quantum Electron. **QE-11**, 317 (1975).
8. B. A. McArthur and J. Tulip, "CO_2 dissociation in sealed rf-excited CO_2 wavequide lasers", Rev. Sci. Instrum. **59**, 712 (1988).
9. W. Haas and T. Kishimoto, "Investigaton of the gas composition in sealed-off RF-excited CO_2 lasers", SPIE proceedings **1276**, 49 (1990).
10. J. A. Macken, S. K. Jagnik, and M. A. Samis, "CO_2 Laser Performance with a Distributed Gold Catalyst", IEEE J. Quantum Electron. **QE-25**, 1965 (1989).
11. U. E. Hochuli and P. R. Haldemann, "Life problems of dc and rf-excited low-power cw CO_2 waveguide lasers", Rev. Sci. Instrum. **57**, 2238 (1986).
12. E. Tsuchida and H. Sato, "Recovery of Transient Gain in an Open-Cycle FAF CO_2 Laser Amplifier Using Gold Catalyst", Jpn. J. Appl. Phys. **29**, L964 (1990).
13. L. A. Newman and R. A. Hart, "Technology Trends in Low- to Medium-Power CO_2 Lasers", SPIE proceedings **36**, 737 (1987).
14. B. T. Upchurch, D. R. Schryer, K. G. Brown, E. J. Kielin, G. B. Hoflund, and S. D. Gardner, "Recent advances in CO_2 laser catalysts", SPIE proceedings **1416**, 21 (1991).

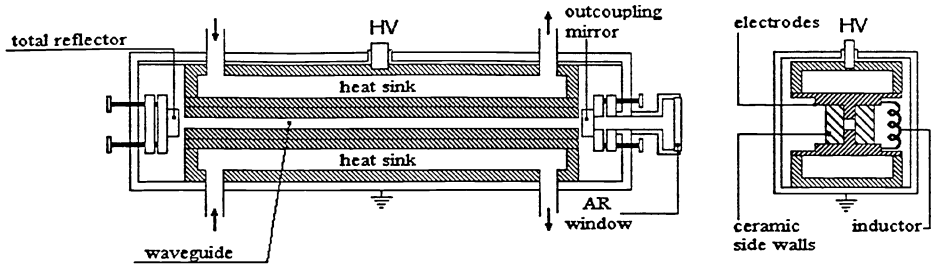

Fig. 1. Schematic of the waveguide laser.

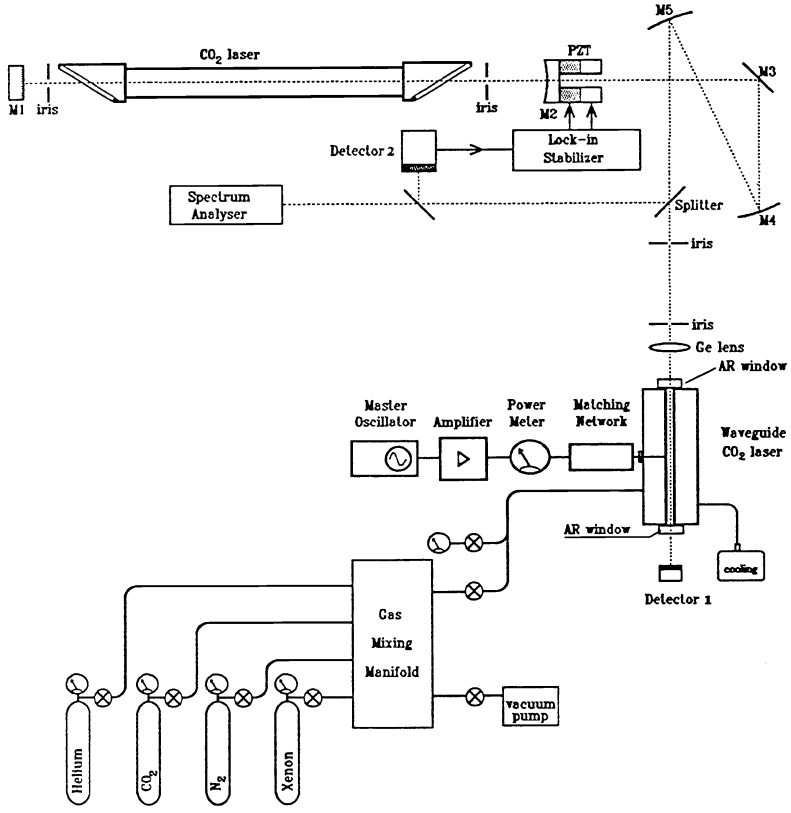

Fig. 2. Schematic diagram of the experimental system, including the set-up for measuring the small-signal gain.

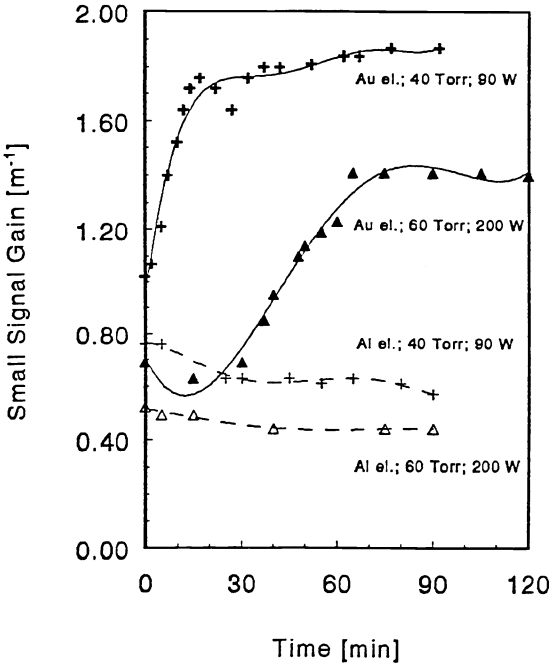

Fig. 3. Small-signal gain as a function of time for the Au and Al electrode materials for 1:1:5+5% (CO_2:N_2:He+Xe) gas mixture composition.

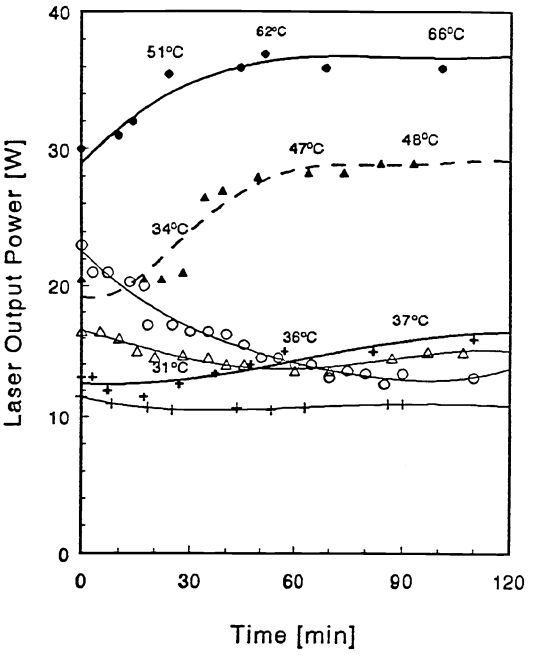

Fig. 4. Laser output power as a function of time for the Au and Al electrode materials using 1:1:5+5% (CO_2:N_2:He+Xe) gas mixture composition at different gas pressures and RF input powers: ✚ - Au el., 40 Torr, 120 W; ▲ - Au el., 60 Torr, 200 W; ● - Au el., 100 Torr, 300 W; + - Al el., 40 Torr, 120 W, Δ - Al el., 60 Torr, 200 W; ○ - Al el., 100 Torr, 300 W. The temperature of the Au-plated non-cooled electrode at about 30, 60 and 90 minutes is also given .

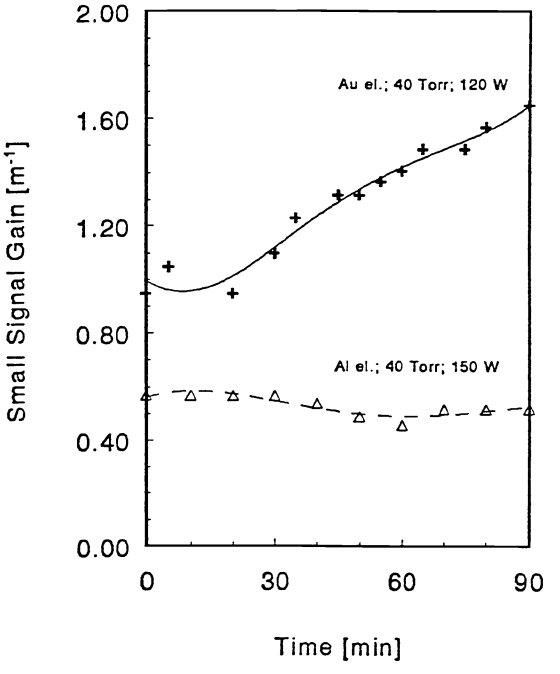

Fig. 5. Small-signal gain as a function of time for the Au and Al electrode materials at 40 Torr of 1:1:3+5% (CO_2:N_2:He+Xe) gas mixture composition. RF input power 120 W and 150 W for the Au-plated and Al electrodes, respectively.

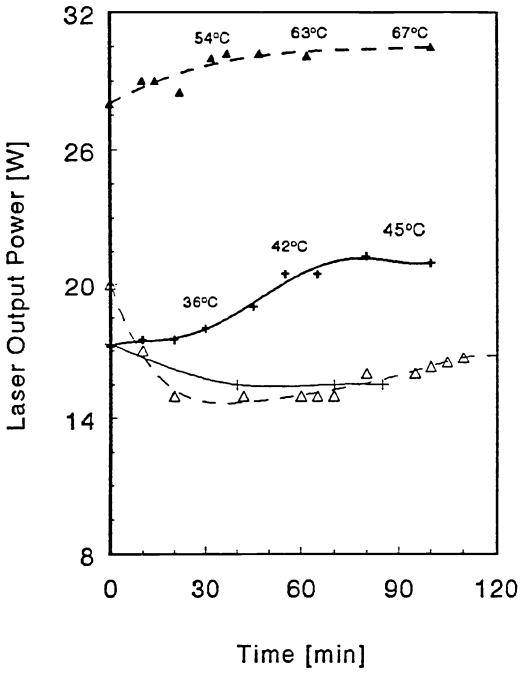

Fig. 6. Laser output power as a function of time for the Al and Au-plated electrodes for 1:1:3+5% (CO_2:N_2:He+Xe) gas mixture at different gas pressures and RF input powers: ✚ - Au el., 40 Torr, 150 W; ▲ - Au el., 80 Torr, 275 W; + - Al el., 40 Torr, 150 W; Δ - Al el., 80 Torr, 275 W. The temperature of the Au-plated non-cooled electrode at about 30, 60 and 90 minutes is also given.

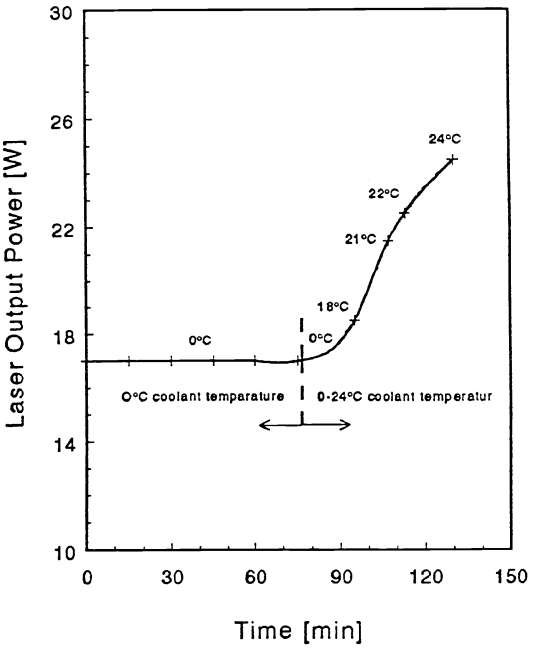

Fig. 7. Laser output power behaviour with time for the Au-plated electrodes in two cooling regimes of the ground electrode at 180 MHz excitation frequency and 60 Torr of 1:1:8+5% (CO_2:N_2:He+Xe) gas mixture.

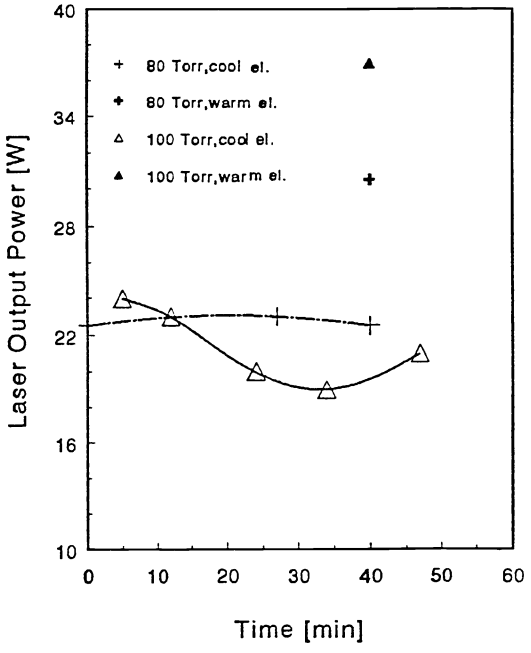

Fig. 8. Laser output power behaviour with time for the Au-plated electrodes, both cooled at about 10°C, at 80 and 100 Torr of 1:1:1:8+5% (CO_2:N_2:He+Xe) gas mixture. The output power, obtained at the same experimental conditions, but with non-cooled top electrode is also illustrated.