Enhanced gain and output power of a sealed-off rf-excited CO_2 waveguide laser with gold-plated electrodes

M. B. Heeman-Ilieva, Yu. B. Udalov, K. Hoen, and W. J. Witteman
Department of Applied Physics, University Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

The small-signal gain and the laser output power have been measured in a cw sealed-off rf-excited CO_2 waveguide laser for two different electrode materials, gold-plated copper and aluminum, at several excitation frequencies, gas pressures and mixture compositions. In the case of the gold-plated electrodes an enhancement of the gain up to a factor of 2 and the output power up to a factor of 1.4 with time at a frequency of 190 MHz and 60 Torr of 1:1:5+5% (CO_2:N_2:He+Xe) mixture is observed. This is believed to be the result of the gold catalytic activities which are favored by increased electrode temperatures and helium rich gas compositions.

During the last two decades rf-excited CO_2 waveguide lasers have received considerable attention[1] because of their compactness, discharge stability, and high output power density of more than 1 W/cm.[2] They are suitable for many applications where long sealed lifetime from a compact device is required. However, the high-power density in a rf discharge causes severe decomposition reactions of the initial CO_2:N_2:He+Xe gas mixture. The main detrimental reactions to the laser performance that produce both the loss of CO_2 and the buildup of O_2 are $CO_2+e \rightarrow CO+O+e$ and/or $CO_2+e \rightarrow CO+O^-$. Since the population inversion is directly related to the number of CO_2 molecules in the upper vibrational level, the dissociation processes of CO_2 will result in a decrease of gain[3-5] and power.[6,7]

In a typical waveguide environment, at high power density and pressure, the initial dissociation of CO_2 molecules per unit volume (when the dissociation is the only process influencing the CO_2 partial pressure) is much higher than in glow discharge systems. This can be seen as follows. The discharge power per unit volume is $P=jE$, where j is the current density and E the field. The electron density is given by $n_e=j/ev_d$. The drift velocity of the electrons v_d is a function of E/p, where p is the gas pressure of the system. Since in the bulk plasma of the discharge E/p remains constant, v_d is also constant. From these considerations it is readily found that n_e is proportional to P/p. The dissociation rate is $kn_e[CO_2]$, where k is the dissociation rate constant and $[CO_2]$ the CO_2 partial pressure for the particular gas mixture and discharge conditions. Thus, the initial fractional CO_2 dissociation is equal to kn_e or proportional to P/p. Since the power density in the waveguide systems is relatively high, this means that the initial fractional CO_2 dissociation, can be reduced at higher pressure. In a sealed-off CO_2 laser, the dissociation of CO_2 proceeds until an equilibrium between the dissociation and reformation processes is reached. There are many factors influencing this equilibrium like gas pressure and mixture, rf input power, electrode material, etc. Typically, about 50%–70% of the CO_2 is dissociated at equilibrium.[8-10]

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. This catalyst must have high activity at ambient laser temperatures, which are generally less than 75 °C, and at low oxygen partial pressures since the only oxygen present in the laser gas is that which is due to CO_2 decomposition. Such a candidate catalyst is gold.[2,9-11] Due to the specific configuration of transverse rf-excited waveguide lasers the internal electrodes are in contact with the active medium along the entire discharge length. Therefore, using a catalytically active electrode surface and a suitable electrode material[9,12,13] strong recombination effects are expected.

In this letter we describe the small-signal gain and output power enhancement caused by gold-plated copper electrodes in comparison with aluminum ones. For the purpose of this investigation the experimental setup used with the laser is essentially the one we described previously[2] except that, besides the gold-plated copper electrodes, an equivalent pair of aluminum electrodes was studied, as well. Briefly, the waveguide structure was metal/ceramic sandwich type with an active discharge volume of $2.5 \times 2.5 \times 370$ mm³. The ratio of the total gas volume to the volume of active region was 1730:1. The laser resonator was formed by two flat mirrors
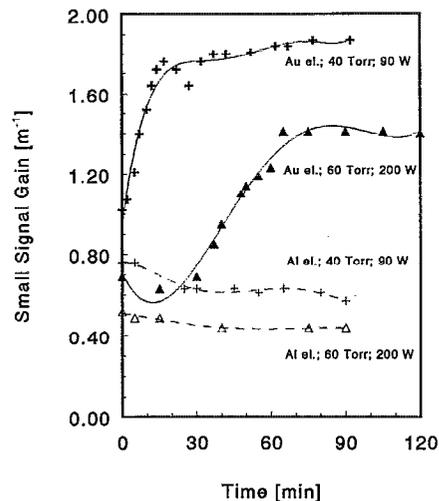

FIG. 1. Small-signal gain as a function of time for the Au and Al electrode materials for 1:1:5+5% (CO_2:N_2:He+Xe) gas mixture composition.
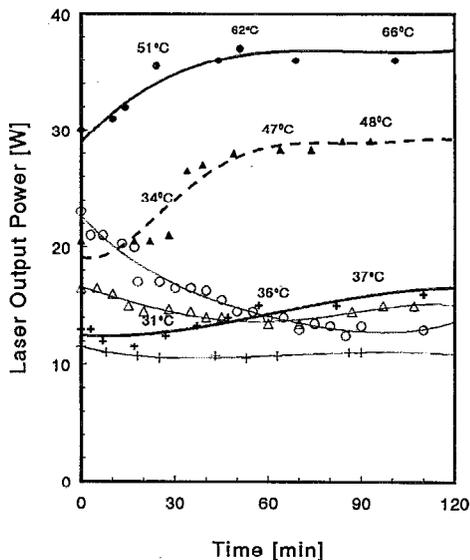
FIG. 2. Laser output power as a function of time for the Au and Al electrode (el.) materials using 1:1:5+5% (CO_2:N_2:He+Xe) gas mixture composition at different gas pressures and rf input powers: (+)—Au el., 40 Torr, 120 W; (▲)—Au el., 60 Torr, 200 W; (●)—Au el., 100 Torr, 300 W; (+)—Al el., 40 Torr, 120 W, (△)—Al el., 60 Torr, 200 W; (○)—Al el., 100 Torr, 300 W. The temperature of the Au-plated noncooled electrode at about 30, 60, and 90 min is also given.

FIG. 4. Laser output power as a function of time for the Al electrodes and Au-plated electrodes (el.) 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; (△)—Al el., 80 Torr, 275 W. The temperature of the Au-plated noncooled electrode at about 30, 60, and 90 min is also given.

with 8.7% outcoupling at one end. The optimized gas mixture was 1:1:5+5% (CO_2:N_2:He+Xe). Unless otherwise indicated, the excitation frequency was 190 MHz. In the present experiments only the ground electrode was cooled (by tap water). The initial temperature of the noncooled upper electrode was about 20 °C, but with time while the discharge was running it reached different steady-state temperatures, depending on the input rf power. For the small-signal gain tests a frequency stable cw CO_2 probe laser was used operating on the $10P(20)$ line and at low output power of,
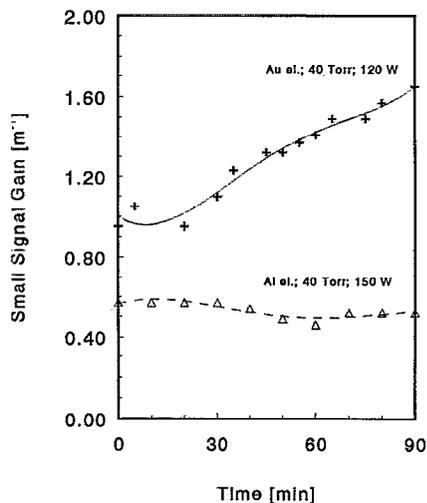

FIG. 3. Small-signal gain as a function of time for the Au and Al electrode materials at 40 Torr of 1:1:3+5% (CO_2:N_2:He+Xe) gas mixture composition. Radio frequency input power: 120 W and 150 W for the Au-plated electrodes and Al electrodes, respectively.

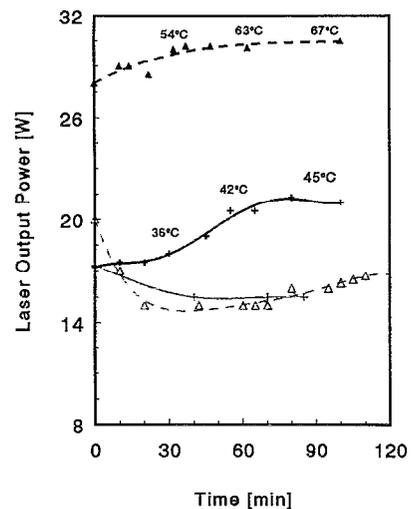typically, 2 W. The single pass gain α_0 was calculated as $\alpha_0 = 1/L \ln(P_1/P_0)$ [m^{-1}], where P_1 and P_0 are the transmitted probe laser powers through the waveguide with and without waveguide discharge, respectively, and L is the discharge length. Measurements of the small-signal gain for both pairs of electrodes at total pressures between 40 and 120 Torr were performed using a mixture 1:1:5+5% (CO_2:N_2:He+Xe). The time variation in α_0 for the tests at 40 and 60 Torr at rf input power of 90 and 200 W, respectively, is shown in Fig. 1. It is seen that the gain with the Au-plated electrodes is much higher, even when the discharge is just turned on. Then it increases markedly (about factor of 2) with time during which heating-up of the noncooled electrode also occurs. The system reaches an equilibrium temperature roughly 80 min after switching on. For the same period of time the gain reaches the highest value. In contrast, the experiments with the Al electrodes show 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. 2 the laser output power behavior with 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 min 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 slight difference in the temperature appeared. It is to be seen that again the Au-plated electrodes cause an increasing output with respect to 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.

It is most likely that the observed phenomena are due to the much stronger catalytic activity of gold than that of aluminum[9] (if any) on the dissociation processes. Contrary to our results, Hass *et al.*[9] presented Al as an electrode surface material superior to gold in recombinational ability. The disagreement in these reports might be attributed to the differences in the experimental conditions. For their investigations, 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. Also, the surface temperature of their waveguide was less than 25 °C, whereas one of our electrodes reaches equilibrium temperatures between 35 and 80 °C, depending on the input rf power. It may be that at higher temperatures the catalytic activity significantly increases. 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 behavior where an increased activity is found at higher temperatures. Whether the same mechanism holds for our surface catalyst is at the moment not known. In addition, one has to consider the inevitable recombination reaction of the CO_2 dissociation products:[3] $CO+OH \rightarrow CO_2 + H$, where OH is formed from water vapor impurities, originating from both the gas supply and the hot electrode surfaces. A different fraction of water vapor bound on the two electrode materials can take place as well.

The enhancement effects of Au-plated electrodes compared to Al ones have also been investigated for 1:1:3+5% gas mixture. Again an increase of gain (Fig. 3) and laser power (Fig. 4) was observed, although less pronounced. A similar behavior is found for this gas mixture at 125-MHz excitation frequency (not illustrated). This is connected to the fact that in gas mixtures with higher CO_2 partial pressures, the fractional dissociation of CO_2 is lower ($\sim P/p$), and consequently a lower enhancement is expected.

In summary a significant improvement of the performance with time of a compact sealed-off rf-excited CO_2 waveguide laser with warm gold-plated electrodes has been achieved.

[1] D. R. Hall and C. A. Hill, *Handbook of Molecular Lasers*, edited by P. K. Cheo (Marcel Dekker, New York, 1987), p. 166.
[2] M. B. Heeman-Ilieva, Yu. B. Udalov, W. J. Witteman, P. J. M. Peters, K. Hoen, and V. N. Ochkin, J. Appl. Phys. **74**, 4786 (1993).
[3] W. J. Witteman, *The CO_2 Laser*, Springer Series in Optical Science (Springer, Berlin, 1987), Vol. 53.
[4] K. J. Siemsen, Appl. Opt. **19**, 818 (1980).
[5] K. J. Siemsen, J. Reid, and C. Dang, IEEE J. Quantum Electron. **QE-16**, 668 (1980).
[6] A. L. S. Smith, T. H. Bett, and P. G. Browne, 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, IEEE J. Quantum Electron. **QE-11**, 317 (1975).
[8] B. A. McArthur and J. Tulip, Rev. Sci. Instrum. **59**, 712 (1988).
[9] W. Haas and T. Kishimoto, SPIE Proc. **1276**, 49 (1990).
[10] J. A. Macken, S. K. Jagnik, and M. A. Samis, IEEE J. Quantum Electron. **QE-25**, 1965 (1989).
[11] E. Tsuchida and H. Sato, Jpn. J. Appl. Phys. **29**, L964 (1990).
[12] U. E. Hochuli and P. R. Haldemann, Rev. Sci. Instrum. **57**, 2238 (1986).
[13] A. L. S. Smith, H. Shields, and A. E. Webb, IEEE J. Quantum Electron. **QE-19**, 815 (1983).
[14] B. T. Upchurch, D. R. Schryer, K. G. Brown, E. J. Kielin, G. B. Hoflund, and S. D. Gardner, SPIE Proc. **1416**, 21 (1991).

Heeman-Ilieva *et al.* 675