Large Aperture CO_2 Laser Discharges

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Abstract—Large aperture high-pressure gas laser discharges are a prerequisite for the development of high-energy gas lasers of sufficient power for the production of plasmas of thermonuclear interest. Of the several approaches being followed toward the attainment of such discharges, one utilizing weak volumetric preionization of the active gas region produced by UV radiation is described. The use of this technique has resulted in the successful generation of atmospheric-pressure CO_2 laser discharges between electrodes separated by 30 cm, having total cross sections of ~600 cm². With input energies of ~200 J/l small signal gain values of 4–5 percent cm^{-1} were measured in 1 : 1 : 3 gas mixtures of CO_2, N_2, and He, respectively. It is thus concluded that this excitation technique could be incorporated into the fabrication of large volume gas laser amplifiers having beam cross sections in excess of 10^3 cm² and total output-energy capabilities of ~ 10^4 J.

I. Introduction

The adoption of transverse electrical excitation techniques in high-pressure molecular gas mixtures has given rise to rapid progress in the development of high-power high-energy gas lasers. As a consequence, much interest has been expressed in the possibility of using such lasers in experiments designed to test the feasibility of producing thermonuclear fusion in laser-produced plasmas. The estimated pulsed laser energy requirements for such experiments have varied considerably, but were until of late typically in the range 10^5–10^7 J. However, recent proposals to utilize up to 10^4 times compression of the plasma, induced by 4π irradiation of a solid or hollow spherical target by a specially tailored laser pulse, have led to several orders of magnitude reduction in these estimates [1], [2]. Nevertheless, the attainment of laser-pulse energies of 10^3–10^5 J with durations of $\lesssim 1$ ns still presents a formidable task, and, before it is achieved, several important aspects must be considered. One of these arises as a consequence of the fundamental limit on the maximum energy which can be transmitted through a given area of the laser medium, established by the threshold energy density for optical breakdown of the medium. For the case of an atmospheric-pressure mixture of CO_2, N_2, and He in the ratio 3 : 2 : 6, this threshold is ~13 J/cm² for a 50-ns duration pulse transmitted through an area of ~5 cm² [3].[1] Consequently, it can be seen that, accepting a suitable safety margin on the maximum tolerable energy density, laser systems capable of delivering sufficient energies will require beam cross sections of at least several thousand square centimeters. By comparison, the largest gas-laser discharge so far reported has a 20- × 10-cm cross section [4]. Although the requirement for individual amplifiers having such large cross sections may be reduced by the employment of several amplifier channels, as has already been adopted in the fabrication of large Nd : glass laser systems [5], clearly the need for the development of large-beam cross-section high-pressure gas laser amplifiers cannot be overemphasized. In addition, the use of large-aperture amplifiers, with beam input energies above that required for gain saturation, minimizes the overall optical gain in the system. This has important benefits in reducing the degree of optical isolation required between amplifier units to prevent self-oscillation, and also in lessening the gain of back-reflected pulses from the plasma and their subsequent effects on optical components in the input stages of the system.

Several approaches to the fabrication of large gas-laser discharges have so far been investigated. The double-discharge schemes of Dumanchin *et al.* [6], and Laflamme [7], which depend upon the production of a weak electron gas in the vicinity of the cathode prior to the main discharge, have been operated successfully with electrodes separated by ~5 cm; and a 10- × 10-cm unit, employing a common anode in the center of the discharge, has been reported [8]. An alternative approach, in which volumetric preionization of the active gas region is produced by a beam of high-energy electrons [9], has also led to impressive results. Electron-beam sources using hot cathode guns have the capability of sustaining discharges for several tens of microseconds (output energies of ~2000 J in 20 μs have been reported [4]), while systems employing field-emission diodes for electron beams are suitable for submicrosecond pumping [10].

Recently, however, several excitation schemes incorporating some degree of initial preionization produced by UV radiation prior to the development of the main discharge have been reported. Created in various types of arc discharges within the laser gas mixture, this radiation is used to illuminate the active region either through a partially transmitting electrode [3], [11], or transverse to the main discharge electrodes [12], [13]. Evidence for the existence of both photoelectric effects associated with the cathode of the main discharge [12], [11], and volumetric photoionization of the active gas region has been obtained [3], [11], [13]. Use of this latter technique has permitted the construction of a laser system having a beam cross section of ~ 60 cm² capable of producing output pulses of ~300 J with peak powers ~3 GW [3].

In the present paper, we wish to describe some studies on the use of UV photoionization as a method of preionizing the laser gas, and in particular, to report the successful

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[1] This threshold value defines the power density at which randomly distributed small isolated plasma points appear in the laser discharge. This estimate is in approximate agreement with precise measurements made over much smaller cross-sectional areas of similar gas mixtures, viz. P. J. Berger and D. C. Smith, "Gas breakdown in the laser as a limitation of pulsed high pressure CO_2 lasers," *Appl. Phys. Lett.*, vol. 21, p. 167, 1972.

operation of discharges in CO_2, N_2, and He mixtures with electrodes separated by 30 cm and total beam cross sections of ~600 cm^2. Input energies of 200 J/l into ~1 : 1 : 3 mixtures of CO_2, N_2, and He, resulted in small signal gain values of 4–5 percent cm^{-1} across major areas of the discharge. The excitation scheme which utilizes a two-dimensional array of high-voltage arcs across a dielectric as a broad-band UV radiation source is simple in construction, does not involve complex vacuum-chamber technology, and lends itself readily to the relatively cheap fabrication of large amplifier units. From these studies, it is concluded that no major problems are involved in the construction of discharge modules based on this excitation technique having beam cross sections in excess of 1000 cm^2, and capable of transmitting short-duration laser pulses with energies ~10^4 J.

II. UV Photoionization of CO_2 Gas Mixtures

The existence of long-range ionizing effects of short wavelength radiation in high-pressure gases has been known for nearly fifty years [14]. Absorption coefficients for UV radiation in various high-pressure gases have been measured by several workers [15]. In addition, the effectiveness of short wavelength radiation in triggering isolated high-pressure arc discharges separated by considerable distances (tens of centimeters) from the UV source has been investigated [16], [17].

The appearance of radiation effects associated wih the excitation of high-pressure CO_2 laser discharges was first noted by Pearson and Lamberton [12]. In their device a discharge between two solid Rogowski profiled electrodes is initiated by the action of an auxiliary discharge which occurs between a fine wire and the anode. Time-resolved photography of the discharge established that the auxiliary discharge occurred some 40 ns or so before the main discharge, which itself was observed to start from the cathode. It was thus concluded that photoemission from the cathode, probably by 584-Å He resonance radiation, was the initiating mechanism of the discharge [12].

However, the first confirmation of the production of uniform volumetric photoionization by radiation from auxiliary discharges in a CO_2 laser discharge was reported by Richardson *et al.* [3]. In this study of a discharge scheme incorporating an auxiliary array of UV producing arc discharges, situated behind one of the main discharge electrodes, nanosecond streak photography of the discharge region identified a condition of weak partial ionization, prior to the main energizing discharge. The onset of this weak ionization occurred within ~10 ns, concurrent with the creation of the auxiliary high-voltage arcs. Subsequently, Judd reported the production of uniform discharges in CO_2 laser gas mixtures using radiation from resistively loaded arcs illuminating transverse to the plane containing the electrodes [13]. The UV preionized devices mentioned above all operate with E/P values for the main discharge equal to or greater than that required to produce a uniform Townsend discharge. This can be compared to the case of the electron-beam-controlled laser, in which sufficient electron-ion pairs are produced by the electron beam to sustain a discharge under almost stable conditions, with electric-field strengths significantly less than those required for a self-sustaining discharge. However, if the effectiveness of UV irradiation of gas mixtures can be increased, discharges incorporating this preionization technique can be operated under similar conditions. Seeding of the laser gas mixture with a metal vapor or a suitable gas having a low ionization potential, and optical pumping of these additives with conventional flashlamps, has been proposed as a means of achieving this condition [18], [19]. Recently, Levine and Javan have demonstrated this technique by operating a small unit with E/P values less than those required for a self-sustaining discharge [20].

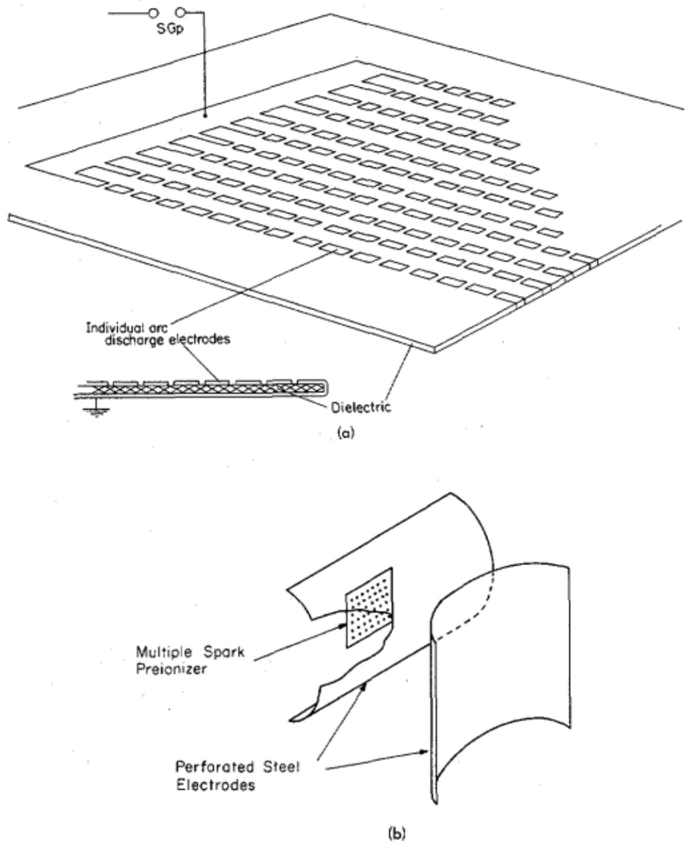

Fig. 1. Schematic diagram of the electrode configuration. (a) The preionizer electrode. (b) The preionizer electrode situated behind one of the main discharge electrodes.

In the high-power UV preionized CO_2 laser system previously reported [3], each discharge module utilized a common stored energy source (a two-stage Marx Bank generator) for both the preionizing discharge, and the main volume discharge in the laser gas mixture. Moreover, the small isolated high-voltage arcs, which provided the UV radiation necessary to photoionize the active gas region, utilized the anode of the main discharge as a common electrode. This facilitated the use of simpler excitation circuitry with less synchronization problems. However, in the present study the preionizing electrode and its circuitry have been isolated from the main discharge circuit.

The type of preionizer electrode used in these experiments is illustrated in Fig. 1(a). It consisted of a two-

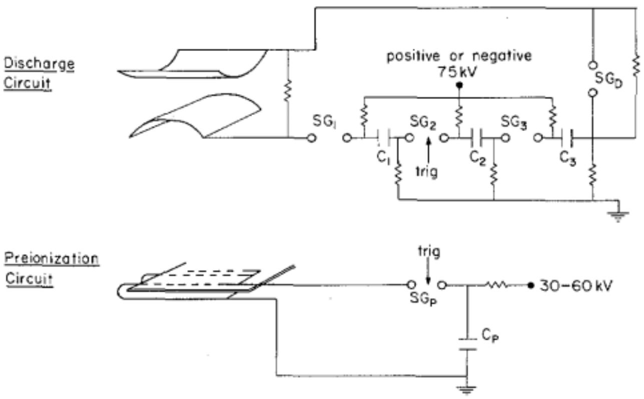

Fig. 2. Excitation circuits of the main discharge and of the preionizer. Legend: SG_1, SG_2, SG_3—high-pressure spark gaps for Marx bank; C_1, C_2, C_3, C_p—0.05- or 0.1-μF low-inductance (20 nH) capacitors; SG_D—high-pressure delay spark gap; SG_P—spark gap.

dimensional array of a large number of arc discharges across a dielectric. The electrode used in obtaining most of the results reported here consisted of ~160 arcs distributed over an area of ~600 cm². A number of linear arrays of arcs in series between copper electrodes were arranged in parallel across a thin sheet of dielectric (fiberglass amalgam) and, for each row of arcs, a low-inductance ground plane was situated beneath the dielectric.[2] The width of each arc electrode was ~4 mm, the arc distance being ~3 mm; no systematic attempt was made to optimize these parameters. The energy dissipated in each row of arcs was 2–6 J provided by switching a low-inductance (20 nH) high-voltage (30–60 kV) 0.1-μF capacitor with a triggered high-pressure N_2 spark gap, as shown in the circuit diagram of Fig. 2. Several locations of the preionizer electrode vis-a-vis the discharge electrodes were examined, including illumination transverse to the main discharge. However, it was found that the most effective position of the preionizer was as is shown in Fig. 1(b), situated immediately behind one of the main electrodes.

III. Discharge Electrodes and Circuit

The majority of the experiments were performed with the electrode configuration shown in Fig. 1(b). The main discharge occurred between two curved perforated electrodes having a transmission factor of 30-40 percent. They were made of 1/16th-in-thick steel having circular perforations of 3.2- or 2.3-mm diameter. The electrodes were oriented orthogonally to one another, as shown in Fig. 1(b), in order to provide a smoothly varying field gradient at the edges of the discharge, and the base size of the electrode was 3–4 times the discharge size. Little precision was involved in the contouring of these electrodes, but in general the central region, where the discharge occurred, was flat and the edges had an approximate Rogowski profile. This construction and configuration of the electrodes permitted the easy fabrication of a number of electrode pairs of different profiles and sizes, thus facilitating the easy investigation of discharge characteristics for a number of electrode separations.

The discharge which occurred between these electrodes was energized by a low-inductance two- or three-stage Marx bank, as shown in Fig. 2. The Marx bank utilized pressurized nitrogen spark gaps, and was triggered in synchronism with the spark gap of the preionizer electrode. However, an additional spark gap (SG_D) was inserted in series with the Marx bank, and its self-breakdown conditions adjusted, so as to provide an adjustable delay between the occurrence of the preionizing arcs and the onset of the main discharge.

Although the results to be reported in Section IV were obtained with the electrodes and configuration described above, several other electrode arrangements were also examined. In particular, the use of solid circularly symmetric electrodes with appropriate profiles, and transverse UV irradiation was studied. Electrodes of different materials, including graphite-covered aluminum electrodes, were used. In general, for large electrode separations, > 10 cm, and rich molecular gas mixtures, > 10 percent (CO_2 + N_2) gas concentration, the transverse method of irradiation was found to be ineffective because of the necessity of locating the radiation source at least 50 cm from the center of the discharge, in order to prevent preferential arcing between the electrodes and the preionizer electrode. The effective "range" of the photoionizing effect appeared to be somewhat shorter than this distance. In addition, it was found that, even for relatively small values of electrode separations, ~5 cm, screening off either or both electrodes from direct view of the preionizer made little difference to the discharge conditions. The nature of the material of either of the electrodes was similarly ineffectual on the discharge. Thus it is considered that with this type of preionizer electrode and this electrode configuration, any effects associated with the production of photoelectrons at the cathode induced by the UV radiation must be small, if not negligible, for the electrode separation parameters considered here.

IV. Characteristics of Uniform Discharges as a Function of Electrode Separation

Utilizing the preionizer and electrode configuration illustrated in Fig. 1 and described in Section III, uniform discharges in CO_2, N_2, and He mixtures were produced for several different electrode spacings. In addition, preliminary analyses of these discharges were made using time-integrated and time-resolved photography, and small signal gain measurements on the $P(20)$ line of a CW CO_2 laser were made to determine the gain profiles in planes both parallel and perpendicular to the electrodes.

The principal characteristics of the discharges investigated are summarized in Table I. For each case, the active volume of the discharge was determined by

[2] The choice of the materials for the electrodes and the dielectric was governed chiefly by the availability of double copper-coated electrical circuitboard. However, in more recent experiments, stainless steel electrodes on glass substrates have also been used, with consequently less electrode deterioration.

TABLE I

SUMMARY OF UV PREIONIZED DISCHARGE CHARACTERISTICS

Case	Electrode Separation (cms)	Discharge Volume (litres)	Discharge Area (cm^2)	Marx Bank(a)	Total Energy(b) (joules)	Electric Field (kv/cm)	Input Energy joules/litre	Fractional Pressure of CO_2 and N_2(c)(p)
(i)	10.0	1.00	100	2-stage	280	15.0	280	40%
(ii)	13.3	1.30	130	2-stage	280	11.3	210	25%
(iii)	13.3	1.30	130	3-stage	420	16.9	316	50%
(iv)	16.8	1.97	180	3-stage	420	13.4	213	35%
(v)	20.0	4.86	310	3-stage	844	11.25	174	25%
(vi)	30.0	12.00	600	3-stage	844	7.5	70	14%
(vii)(d)	5.0	1.27	26	2-stage	340	23.0	270	60%

(a) The Marx banks were constructed using low-inductance (20-nH) 0.05- or 0.1-μF capacitors.

(b) This does not include the energy in the preionizer circuit.

(c) This column gives the maximum ($CO_2 + N_2$) composition, with approximately equal fractions of CO_2 and N_2, in which a uniform arc-free discharge could regularly be produced.

(d) This case summarizes the operating characteristics of the UV preionized discharge system described by the authors in [3]. Although significantly less energy was used in the preionization discharge for this electrode separation, nevertheless, the results are complimentary to the recent data.

photography of the latter, and, within the constraints of available low-inductance capacitors, the input energy adjusted so as to have input-energy densities of 200–300 J/l. In addition, by adjustment of the self-breakdown voltage conditions on the additional spark gap (SG_D) in the Marx bank circuit an appropriate delay, typically ~ 2 μs, was inserted between the triggering of the preionizer and the onset of the main discharge. However, the permissible latitude on this value without the discharge becoming unstable was quite large, at least 1 μs. For each particular discharge configuration, the gas composition was varied to determine the maximum partial pressure of combined CO_2 and N_2, in almost equal proportions at which reliable uniform discharges could be repetitively produced without the formation of arcs. Since the small signal gain and the energy extraction of a laser amplifier are related to the percentage CO_2 and N_2 gas composition for a given input energy, the figures given in the last column of Table I give an indirect measure of the potentialities of these discharges as laser amplifiers. In all cases the discharge conditions were not dependent on the polarity of the electrodes. As can be seen, discharges with electrode separations of 20 cm were successfully generated with total beam cross sections of ~ 300 cm^2, and input energies of ~ 200 J/l into 35-percent ($CO_2 + N_2$) gas mixtures. In addition, although the main discharge energy supply placed restrictions on the maximum input energy and applied voltage, reproducible discharges with electrode separations of 30 cm and beam cross sections of ~ 600 cm^2 were successfully generated. A photograph of a typical discharge with this electrode separation is shown in Fig. 3. Since little effort was put into optimizing the electrode profile, it is clear from these results that, with more suitable electrode design, uniform discharges of this electrode spacing or greater, with total cross-sectional areas greater than 10^3 cm^2, may be constructed.

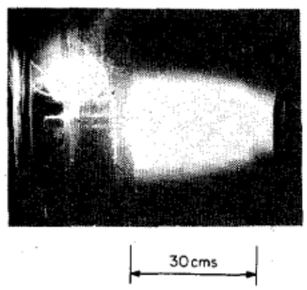

Fig. 3. Time-integrated photograph of atmosphere-pressure discharge in CO_2, N_2, and He gas mixture with electrodes separated by 30 cm. The white circular spot in the left-hand upper corner results from light produced by one of the pressurized spark gaps. The two-dimensional array of preionizing arc discharges can clearly be seen behind one of the perforated electrodes.

Moreover, further analysis of the data presented in Table I indicates that a simple scaling law exists between the maximum partial pressure of CO_2 and N_2 and the electric field applied between the electrodes.

Let p be the maximum fractional partial pressure of CO_2 and N_2, for which reproducible uniform discharges are created, and defined by

$$p = (p_{CO_2} + p_{N_2})/(p_{CO_2} + p_{N_2} + p_{He})$$

where p_{CO_2}, p_{N_2}, and p_{He} are the partial pressures of CO_2, N_2, and He, respectively. Then, if E is the electric field applied between the electrodes during the discharge, the relationship between p and E may be found using the data of Table I. This is shown in Fig. 4 and indicates an approximate two-thirds power law between the maximum fractional pressure and the applied field of the form

$$E = 27.8 p^{2/3} \text{ kV/cm}$$

over the pressure range considered.

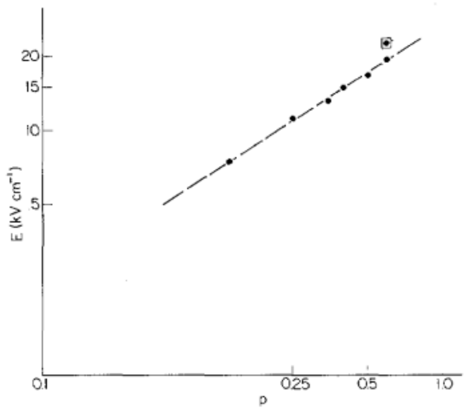

Fig. 4. Relationship between the applied field and the maximum partial pressure of CO_2 and N_2 which can sustain uniform discharges. The point marked with a square corresponds to the system described in [3], and is added for comparison.

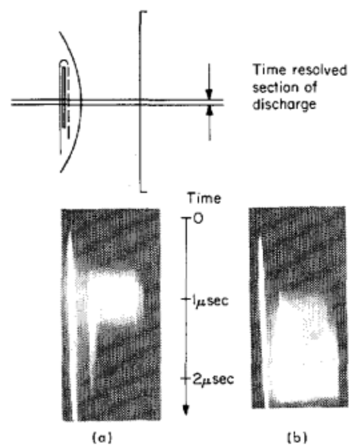

Fig. 5. Time-resolved photographs of the development of the discharge with an electrode separation of 16.8 cm. (a) Normal arc-free discharge. (b) Deliberate formation of an arc between the electrodes.

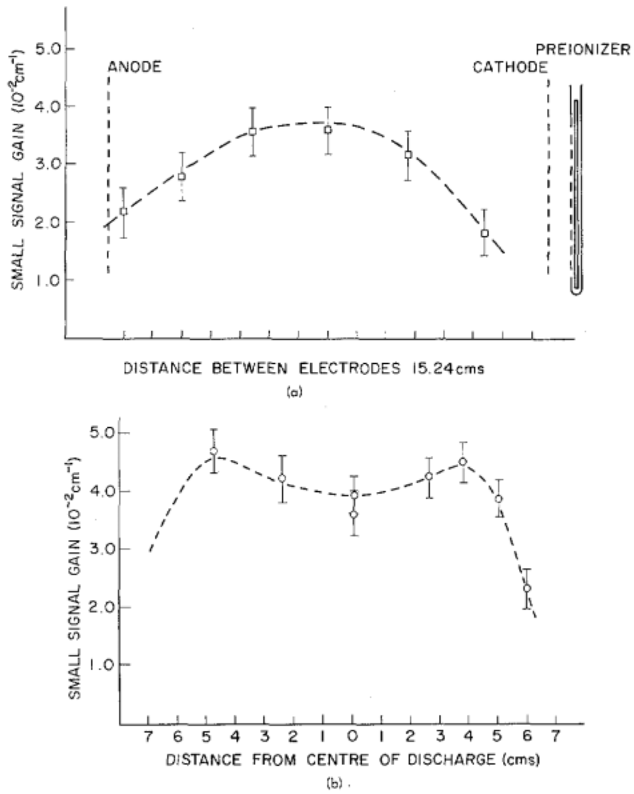

Fig. 6. Small signal gain profiles. (a) Between the electrodes. (b) In a plane parallel to the electrodes, for a discharge with electrodes separated by 15 cm.

Time-resolved photography of the 11.8-cm discharge, Case (iv) of Table I, was undertaken in order to determine some of the temporal aspects of the discharge. The method was similar to that employed with the earlier discharge [3]. An image of the cross section of the discharge was focussed onto a 1-mm slit, and an image of the latter focussed onto the (S20) photocathode of an electrooptic image converter camera. Streak photographs of the discharge were obtained, and two such photographs are shown in Fig. 5. When operated under normal arc-free conditions, the temporal behavior of the discharge was as is shown in Fig. 5(a). The continuous narrow illumination on the left side of the photograph is that resulting from the multiple-arc preionizer. The main discharge occurs ~400 ns after the initiation of the preionizer pulse. Although this delay may be effectively controlled by variation of the self-breakdown conditions of the delay spark gap (SG_D) in series with the Marx bank, it may be varied considerably, up to ~2 μs, without effect on the discharge characteristics. Unfortunately, the brightness of the preionizer made impossible the observation of the weak illumination which results in the active area prior to the main discharge, observed previously [3]. As can be seen, the main discharge has a duration of ~500 ns, which is in close agreement with current measurements made on the earlier discharge using a similar Marx bank [3]. In addition, the occasional existence of small filamentary arcs, emanating from the anode for a distance of 10 mm or so, was noted, and is visible in the photograph of Fig. 5(a). Under conditions insufficient for the support of a uniform discharge, the ensuing arc between the two electrodes was invariably of the form shown in the photograph of Fig. 5(b), in which the arc was created by the fusion of two filamentary avalanches which propagate from each electrode.

Small signal gain measurements were made on the gas medium in a similar manner to that described earlier [3]. The 5-mm diameter, 10-W output of a CW CO_2 laser operating on single line, P(20), was passed through the excited medium, detection of the amplified pulse being made with a Au-doped Ge photoconductive detector in combination with a fast oscilloscope. The duration of the gain pulse was similar to that previously observed, the pulse having an initial rise time of <1 μs and a fall time of 4–5 μs. By passing the CW laser beam through different sections of the discharge medium, the spatial gain profiles, both between the electrodes and on the central plane parallel to them, were deduced. The profiles obtained for the discharge produced between electrodes spaced 15 cm apart are shown in Fig. 6. These show that the gain distribution about the center of the discharge is symmetrical with peak values in the region of 4–5 percent. The apparent rapid falloff of the gain in the vicinity of the electrodes most probably results from the assumption of a discharge volume having an exactly rectangular cross section. As can be seen from Fig. 3, this is not strictly the case. However, the double-peaked gain distribution observed in the plane parallel to the electrodes cannot be explained by this assumption, as the discharge would be expected to approach a circular cross section in this region. Although the distribution cannot readily be explained, it may well indicate some gain inhomogeneity in the discharge resulting as a consequence of incorrect profiling of the electrodes.

V. Conclusions

These initial studies offer some encouragement to the possibility of utilizing this excitation mechanism for the production of large-aperture high-pressure discharges suitable for high-power laser systems. In making comparisons between this approach and the use of electron-beam preionization, the latter method still has an advantage in its ability to operate at voltages below the self-sustaining limit. However, the relative simplicity of the photoionization approach, which is significantly less costly, is attractive. Its adoption need not be limited to the excitation of CO_2 laser gas mixtures, and may well be useful for gas mixtures at pressures greater than 1 atm.

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