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Generation of a uniform high-density microwave plasma for CO_2 lasers using orthogonal electric fields

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ABSTRACT To realize a CO_2 laser using a fast-axial-flow high-output-power microwave discharge excitation, we devised a technology for making the microwave discharge uniform by varying the oscillation direction of an electric field with time. We also verified the effectiveness of this technology. As a result, we succeeded in increasing the discharge uniformity to 70% of the laser-tube cross-sectional area and realized a high laser output power and a high laser efficiency. In the case of a microwave input power of 1450 W, a maximum laser output power of 273 W and a laser efficiency of 18.8% were achieved; in the case of a microwave input power of 1070 W, a laser output power of 214 W and a laser efficiency of 20.0% were achieved. At the time of maximum output power, a high input power density of 280 W/cm^3, which is approximately 20 times that in a dc discharge method, was achieved. Thus, a high-output-power microwave-discharge-excited CO_2 laser has become feasible.

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1 Introduction

The use of CO_2 lasers has become widespread for cutting and welding of sheet metal, because they have excellent thermal processability with a high laser output power and a high laser efficiency. In recent years, CO_2 lasers have also attracted attention as lasers for processing electronic parts. Methods of laser gas cooling and discharge excitation, such as gas-flow dc, gas-flow rf [1], slab rf [2–5], gas-flow microwave [6–14], and slab microwave [14–18] are used. Microwave-discharge-excited CO_2 lasers have several characteristics, including clean gas systems due to the use of no-electrode-discharge excitation, the possibility of miniaturization due to their high input power density, electrical safety because their waveguide surface is grounded, and inexpensive power sources due to the use of magnetrons.

However, it is more difficult to generate a uniform microwave discharge [19, 20] compared with rf discharges [1], which have a sheath with a capacitive ballast effect. When a uniform discharge is not generated in the laser beam cross-sectional area, the efficiency of laser gas utilization decreases. With a microwave discharge, because streamer discharge is easily generated at a high gas pressure, it is difficult to increase laser efficiency. Consequently, a practical high-output-power CO_2 laser using microwave discharge excitation has not yet been realized.

In this study, using the configuration of a fast-axial-flow CO_2 laser, the microwave discharge was spatially uniformly spread in the direction of the laser-tube cross-sectional area while the generation of streamer discharge was suppressed. In this manner, a stable discharge over time was realized. With this achievement, a CO_2 laser with a high input power density and a high laser efficiency could be realized.

2 Method of making discharge uniform

Streamer discharge tends to occur and grow when the supplied electric field oscillates in only one direction. Therefore, if the oscillation direction of the electric field is varied before the generation and growth of streamer discharge, stable and uniform discharge in terms of time and space can be obtained. To vary the oscillation direction of the electric field with time, microwaves that oscillate in two different directions in the same plane are overlapped with the oscillation directions of their electric fields, mutually orthogonal at the optical axis of a laser tube. The oscillation directions of the electric field vectors are rotated in the cross section of the laser tube.

Figure 1 shows a schematic of the principle of the orthogonal electric fields method. The phase difference between the electric fields of a horizontal microwave (E_H) and a vertical microwave (E_V) is 90°. Consequently, the oscillation direction of the electric field vector rotates with the oscillation frequency of the magnetron at 2.45 GHz, making the discharge uniform.

To achieve circular polarization, the following steps are required: splitting the microwave power generated by one magnetron into two separate paths, introducing a phase shift of 90°, and spatially superimposing the fields orthogonally. However, with such a configuration, problems such as mu-

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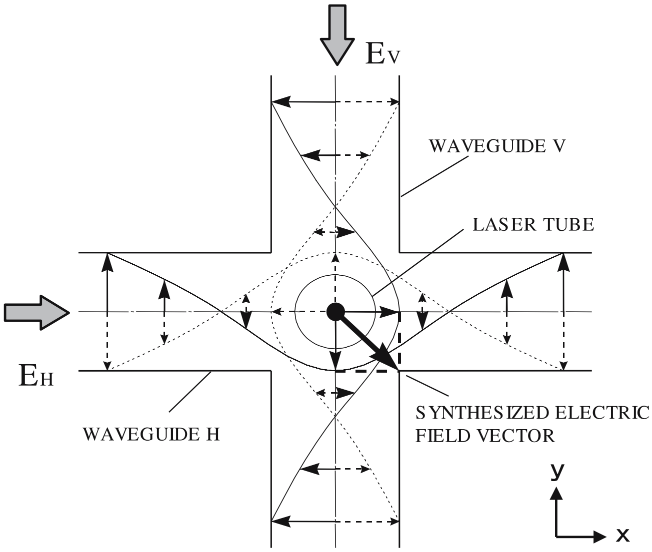

FIGURE 1 Cross-sectional view of waveguides used in the orthogonal electric fields method

tual interference by the divided or reflected microwaves occur, hindering the stable operation of the magnetron. Therefore, in the verification of the principle, we used two magnetrons so that each microwave propagation system was independent, and we supplied microwaves into the laser tube from two orthogonal directions.

In the design of the orthogonal electric fields method, the microwave emitted from magnetron H on waveguide H must not affect the performance of magnetron V on waveguide V. The crosstalk between the horizontal waveguide and the vertical waveguides was analyzed using the electromagnetic-wave-analysis simulator (MACS-3D) [21]. Figure 2a shows the analysis area, and 2b shows the analytical results. Three-dimensional models were used for analysis. A microwave source was assumed to be located in a horizontal waveguide, and the distributions of the electric field intensity in waveguides were analyzed. At the intersection of the waveguides, an antinode of the standing wave was formed. We confirmed that there was no crosstalk between the horizontal waveguide and the vertical waveguide by simulating an electromagnetic wave.

Since the two magnetrons have individual variabilities, a difference of 10–20 MHz between their oscillation frequencies exists. The phases of the two electric fields vary with time due to this frequency difference. When two microwaves that have mutually orthogonal oscillation directions, and variable phases over time are synthesized, the locus of the synthesized electric field repeatedly changes as follows: straight line → ellipse → circle → ellipse → straight line. Even when the electric field vector resulting from su-

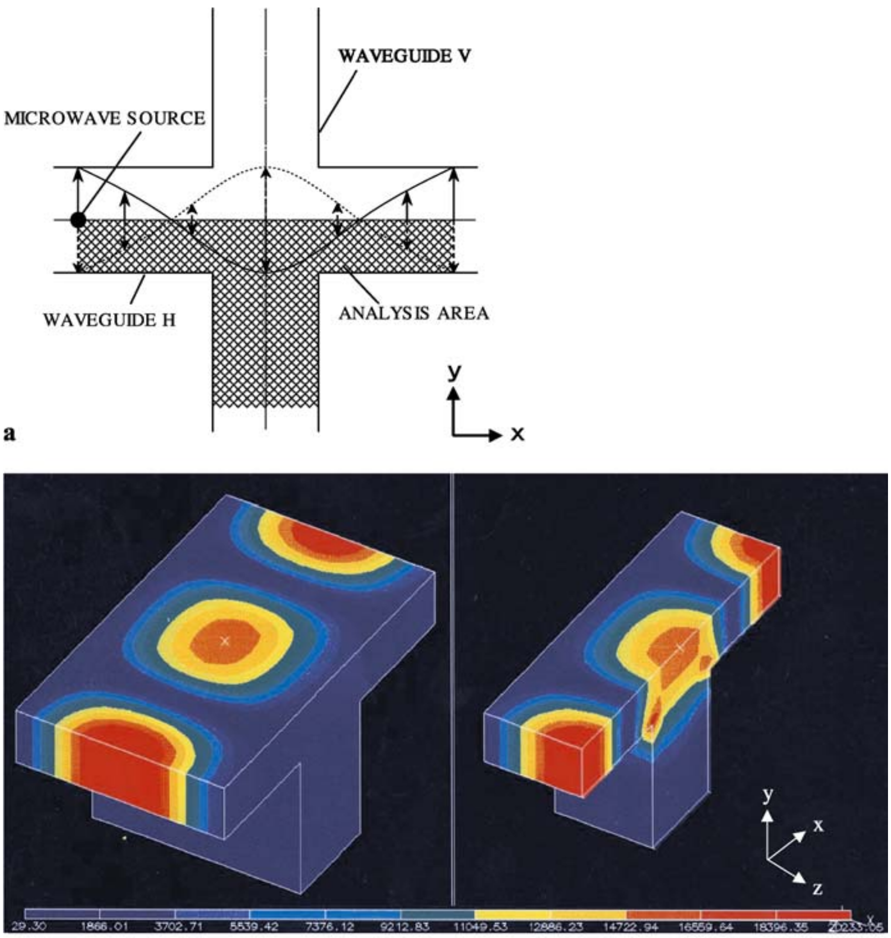

FIGURE 2 (**a**) Cross-sectional view of the analyzed area of the electromagnetic wave analytic simulator. (**b**) Result of the analysis of an electromagnetic wave

perposition is changed from a line to an ellipse to a circle, the electric field is nearly equivalent to a circular polarization with a frequency of 10–20 MHz. Therefore, a uniform discharge can be achieved while preventing the generation and growth of streamer discharge.

3 Experimental procedure

Figure 3 shows the configuration for the orthogonal electric fields method. A microwave, which propagates inside the rectangular waveguide in the TE_{10} mode, is emitted by a magnetron (2M244). The oscillation frequency of the magnetron is 2.45 GHz. The dimensions of the rectangular waveguide are 45 mm × 95 mm. Under these conditions, the wavelength in the waveguide becomes 159 mm. The two magnetrons are synchronized in terms of pulse repetition time. The magnetrons are operated in a pulse mode under the conditions of a duty cycle of 25 kHz and a 20% repetition rate. The maximum output power of the microwave from a magnetron is a mean power of 800 W and a peak power of 4 KW, and adjustable. The travelling wave and reflected wave of a microwave are separated by a directional coupler. The electric field strength of the microwave is measured using a microwave power monitor with a detection diode. The peak-output powers of microwaves are adjusted to be equal in magnitude by monitoring the oscilloscope. The average power of a microwave is measured using a microwave power meter (HP437, HP8481A). A standing wave of the microwave electric field results from resonance between a stub tuner and a reflection plate. A laser tube is located at the maximum electric field strength along the standing wave pattern, and a stable glow discharge is maintained inside the laser gas. Using three stub tuners, impedance matching with a discharge load is achieved with voltage standing wave ratio (VSWR) below 1.3. The laser beam is emitted orthogonally to the propagation direction of the microwave.

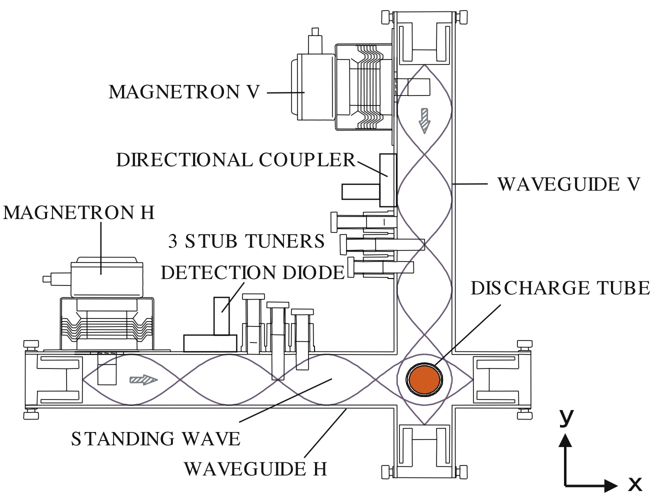

FIGURE 3 Cross-sectional view of laser tube used in two-magnetron orthogonal electric fields method

Figure 4 shows the configuration of the discharge system, gas circulation system, optical system and measurement system. Two microwaves propagate in the x and y directions. A laser tube is inserted perpendicular to the x–y-plane. The gas circulation system adopts a fast axial flow, and laser gas is circulated by a mechanical booster pump (ULVAC PMB012C). The diameter of the laser tube made of quartz glass is 25 mm, its length is 636 mm, and the laser-gas pressure in the discharge section is 1.07×10^4 Pa. As the laser gas, we use a mixed gas of He, N_2 and CO_2. The gas composition is He : N_2 : CO_2 = 72 : 24 : 4. The laser gas flow velocity is 300 m/s. The distance that the laser gas moves until the time the discharge is turned off is about 12 mm. As the optical resonator, we use an AR-coated ZnSe output mirror with a reflectivity of 95% and a radius of curvature of 10 m, and a flat AR-coated ZnSe reflective mirror with a reflectivity of 99.5%; the length of the resonator is 1 m. Laser output power is measured using a laser power meter (OPHIR 1500W-MD). The discharge-brightness distribution in the cross-sectional area of the laser tube is measured using a beam profile analyzer (Big Sky Laser Technology, Inc., Beam View Analyzer PLUS) with a CCD camera (PULNIX TM-7CN).

4 Experimental results and discussion

Figure 5 shows the discharge-brightness distribution in the cross section of the laser tube obtained using the orthogonal electric fields method. The black circular line cen-

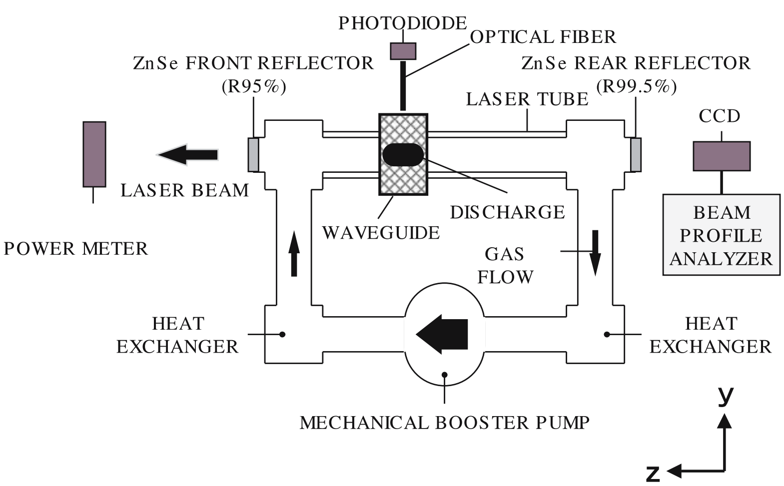

FIGURE 4 Schematic structure of CO_2 laser system for microwave discharge and measurement

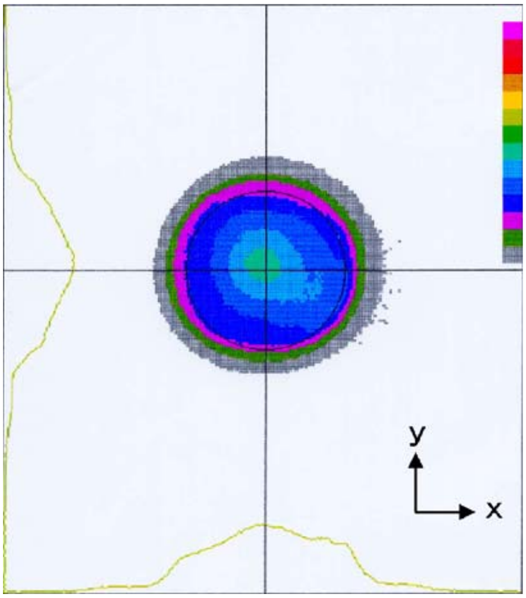

FIGURE 5 Electric discharge brightness distribution in laser tube cross section obtained by two-magnetron orthogonal electric fields method

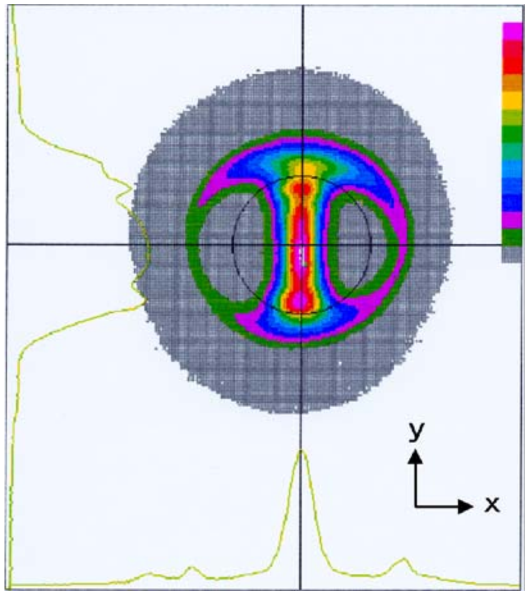

FIGURE 6 Electric discharge brightness distribution in laser tube cross section using the unidirectional electric field method

tered on the main axis is the location of the discharge region on the laser tube inner wall. The light of the discharge is reflected in the laser tube from the discharge region to a rear reflector. It is the brightness distribution outside the black circular line. When this method is used, uniform discharge is generated in the cross-sectional area of the laser tube. The discharge uniformity is evaluated using the mean value of discharge brightness over the entire cross section of the laser tube normalized by the maximum brightness. According to the measurement using the beam profiler, the discharge area spreads significantly uniformly with a discharge uniformity of 70%.

For comparison, we performed similar experiments using only one magnetron and one waveguide (unidirectional electric field method). Figure 6 shows the discharge-brightness distribution measured using the beam profiler. Regarding the shape of the discharge, the part with a high discharge strength has a thin belt shape in the oscillation direction of the electric field at the center of the cross section of the laser tube. The area of useful discharge for the unidirectional electric field method is small and has a discharge uniformity of 40%. In this case, a number of thin streamers are generated in the direction of the electric field, which induces a decrease in excitation efficiency.

Figure 7 shows the characteristics of laser input/output powers using the orthogonal electric fields method. Regarding the laser efficiency, a maximum laser output power of 273 W and a laser efficiency of 18.8% were obtained for an average microwave input power of 1450 W. In addition, a laser output power of 214 W and a laser efficiency of 20.0% were obtained for an average microwave input power of 1070 W.

The laser efficiency obtained by the unidirectional electric field method saturated at a maximum laser output power of 130 W and a laser efficiency of 14.3% for a microwave input power of 910 W. Decreases in the input power and in the laser efficiency as compared with the case of orthogonal electric fields, occurred due to a low degree of spread of the discharge with a discharge uniformity of 40% and due to the generation and growth of streamer discharge.

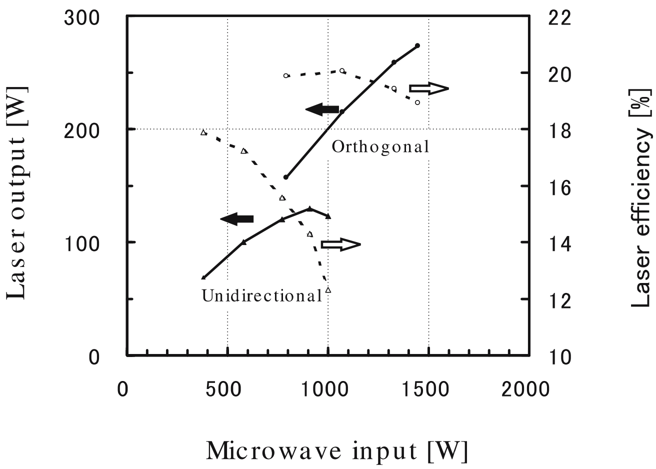

FIGURE 7 Laser output power and laser efficiency as function of microwave input power for unidirectional electric field method and orthogonal electric fields method

The discharge-brightness distribution was determined using an avalanche photodiode to measure discharge length in the laser-tube direction. Figure 8 shows the results of the electric discharge brightness measurement in the long axis direction of the laser tube. When it is normalized with maximum brightness, even if discharge brightness changes with the input power, it has almost the same distribution. The discharge length is approximately 15 mm based on the full width at half maximum, and the input power density reaches 280 W/cm^3. At this time, the discharge region for every pulse is overlapped 20% with the gas region of the previous pulse discharge in full width at half maximum. The length of the active area is estimated to be 120 mm from the lifetimes of the excited N_2 and CO_2 vibrational states and the gas flow rate. A very high input power density was obtained by the orthogonal electric fields method.

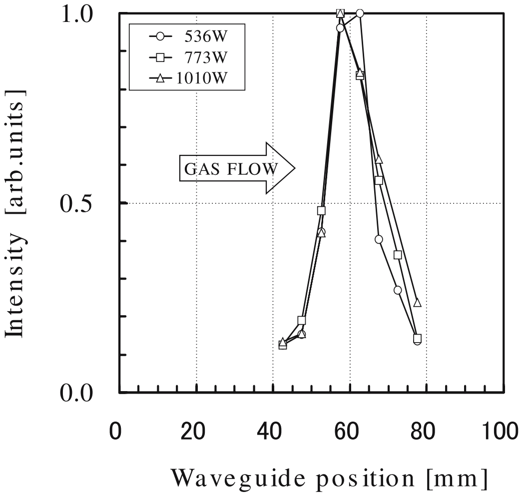

FIGURE 8 Electric discharge brightness distributions in the waveguide position at different microwave input powers

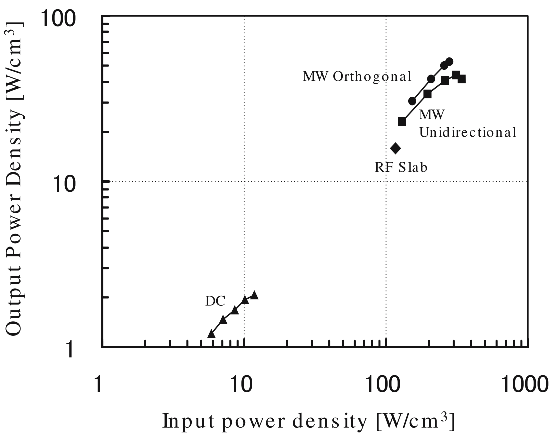

FIGURE 9 Relationship between input power density and output power density for dc discharge method and microwave methods

Figure 9 shows the relationships between input power density and laser output power density for the case of a fast-axial-flow dc discharge excitation laser, the case of the fast-axial-flow microwave discharge excitation lasers and the case of a slab rf [5] excited laser. With the orthogonal electric fields method, input power density and laser output power density approximately 20 times higher than those with dc discharge excitation were achieved. Furthermore, with the orthogonal electric fields method, the laser output power obtained from a unit discharge volume was improved by approximately 20% compared with the case of the unidirectional electric field method.

If circular polarization could be realized by a single magnetron, further fast rotation of the oscillation direction of the electric field would become possible, and both the discharge area and the stability would increase. We set the length of the waveguide at two wavelengths; however, a 1.5-wavelength resonator system can easily be designed. In addition, by bending the waveguide, a compact design is also possible.

5 Conclusions

For microwave discharge excitation, we devised an orthogonal electric fields method in which the oscillation direction of the electric field is varied with time, and we verified the effectiveness of the method. With the orthogonal electric fields method, discharge can be uniformly spread throughout the cross-sectional area of a laser tube to a discharge uniformity of 70%, and a stable discharge can be obtained while suppressing the generation and growth of streamer discharge. At a laser gas pressure of 1.07×10^4 Pa, a maximum output power of 273 W and laser efficiency of 18.8% were obtained for a microwave input power of 1450 W. For a microwave input power of 1070 W, an output power of 214 W and a laser efficiency of 20.0% were obtained, resulting in a high laser output power and a high laser efficiency. In addition, in microwave discharge excitation using the orthogonal electric fields method, we achieved a high input power density of 280 W/cm^3, which is approximately 20 times that of dc discharge. Thus, the realization of a CO_2 laser using high-output-power microwave discharge excitation has become possible.

In the future, we will pursue high laser output power using multiple microwave-discharge units, and will perform the evaluation of the laser beam quality and laser processing.

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