Development of longitudinally excited CO\textsubscript{2} laser

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Abstract. Simple, compact, and affordable discharged-pumped CO\textsubscript{2} laser controlled by a fast high voltage solid state switch has been developed. In this study, longitudinal excitation scheme has been adapted for simple configuration. In the longitudinal excitation scheme, the discharge is produced along the direction of the laser axis, and the electrodes are well separated with a small discharge cross-section. Triggered spark gap switch is usually used to switch out the high voltage because of simple and low cost. However, the triggered spark gap switch operates in the arc mode and suffer from recovery problem causing a short life time and low efficiency for high repetition rate operation. As a result, there is now considerable interest in replacing triggered spark gap switch with solid state switches. Solid state switches have significant advantages compared to triggered spark gap switch which include longer service lifetime, low cost and stable high trigger pulse. We have developed simple and low cost fast high voltage solid state switch that consists of series connected-MOSFETs. It has been installed to the longitudinally excited CO\textsubscript{2} laser to realize the gap switch less operation. Characteristics of laser oscillation by varying the discharge length, charging voltage, capacitance and gas pressure have been evaluated. Longer discharge length produce high power of laser oscillation. Optimum charging voltage and gas pressure were existed for longitudinally excited CO\textsubscript{2} laser.

1. Introduction

Nowadays, lasers are applied in many industrial processes. CO\textsubscript{2} laser is a gas laser that produces a strong infrared light with the principle wavelength bands ranging from on 9.2 to 11.4\textmu m. The excitation schemes used for CO\textsubscript{2} lasers are classified into two according to the structure of the laser tube which are longitudinal excitation scheme and transverse excitation scheme. Pulse discharge, DC discharge and RF discharge are used for the pumping of CO\textsubscript{2} laser.

Here, we focus on the longitudinal excitation scheme pumped by a pulse discharge [1]. In the longitudinal excitation scheme, discharge is produce in the direction of the laser axis, and the electrodes are well separated and give small discharge cross-section. The long discharge length provides a high breakdown voltage at low gas pressure. Laser oscillation at low pressure can be allowed by the uniform discharge due to the fast electron drift velocity. Moreover, the discharge uniformity is not affected by residual charge in the longitudinal excitation because a discharge takes place in a discharge tube with a long length [1-5].

Thyratrons or spark gaps switch have been used in many applications as a discharge switch to switch out of several tens of kilovolts. However, the thyratrons which are expensive and have the life time problem whereas the spark gap switches operate in the arc mode and suffer from recovery
problem causing a short life time and low efficiency for high repetition rate operation. Therefore, these switches are being phased out.

Solution to those problems, in recent years, improvement of power semiconductor technology contribute to a major advanced towards highly reliable industrial laser systems since solid state switches are maintenance free and have long life time. In this case, spark gap switch can be eliminated entirely by the use of solid state switch by modern semiconductor switches such as IGBTs and MOSFETs.

2. Experimental

2.1 Longitudinal excitation scheme

The longitudinally discharged-pumped CO₂ laser controlled by a fast high voltage solid state switch is schematically shown in Fig. 1, consisting of high voltage DC power supply, diode, charging resistor, capacitor, discharge tube, and fast high voltage solid state switch. A mixed (CO₂: 70% N₂: 14% He: 79%) gas is filled in a 30 cm and 40 cm-long pyrex tubes with an inner and outer diameter of 10 mm and 14 mm, respectively. Metallic electrodes were attached to the both ends of the laser tube. High reflective mirror and ZnSe output coupler with reflectivity of 70% formed a resonator.

![Figure 1. Schematic diagram of longitudinally excited CO₂ laser controlled by a fast high voltage solid state switch](image)

Trigger electrode was made of copper sheet with width of 15 mm and wrapped at the outer wall of the discharge tube. Trigger electrode locates between two main electrodes, is connected with the solid state switch and labelled as T as shown in Fig. 1. The fast high voltage solid state switch indicated in Fig. 1, is operated as a trigger switch. This scheme realizes simple construction of gas laser excitation without discharge switch like a spark gap.
2.2 Fast high voltage solid state switch

The fast high voltage solid state switch that consists of avalanche transistor and series-connected MOSFETs has been developed. An avalanche transistor circuit is used as the gate driver. Connecting several MOSFETs in series allows fast switching time with working-voltages of several kilovolts can be realized [6]. Zener diode between gate and source prevents breaking down of the gate by high voltage pulse [7].

5 kV of DC voltage $E_2$ is applied from DC power supply to the MOSFETs. The voltage of each MOSFET is divided by the resistances which are connected between drain and source of the MOSFET. At the same time, capacitors are charged. By applying a voltage of 300 V, avalanche breakdown occurs in the avalanche transistor (2N5551). The avalanche transistor produce fast signal in several nanoseconds. This fast pulse charges the input capacitance of the MOSFET (M1) quickly.

When the bottom gate of the M1 turns on, the voltage difference, $V_1$ is generated between ground and the source of M2. $V_1$ is divided by C2 and the input capacitance of M2. The capacitor that connected between gate terminals of every MOSFET is discharge from C2 to C5, and turned on the MOSFETs from M2 to M5 in sequence, finally switch out the high voltage. Fast high voltage solid state switch is triggered as a spiker that produce pre-ionization in laser tube and voltage pulse to initiate the discharge.

This fast high voltage solid state switch capable to deliver fast pulse in 40 ns at 5 kV voltage. This circuit is compact and less expensive since a drive circuit for each gate does not required.

2.3 Laser Oscillations

DC voltage, $E_1$ was applied to the discharge tube. Capacitor C connected parallel with the discharge tube as shown in Fig. 1 was charged by the current that flows from $E_1$. At the same time, positive voltage pulse generated by pulse generator was used to trigger the fast high voltage solid state switch. $E_2$ was set to be 5 kV. When the fast high voltage solid state switch is switched, the discharge is induced in the glass tube producing laser oscillation.

In this experiment, laser output energy was measured with an energy detector (Gentex ED-200), and the voltage waveform was measured with a high voltage probe coupled with an oscilloscope (Tektronik TDS 3054C).

3. Results and Discussion

30 cm and 40 cm-long tubes have needed at least 10 kV and 20 kV charging voltage, respectively to produce laser oscillation. Characteristic of laser output energy was examined under some parameters which are charging voltage, capacitance C, gas pressure and capacitance between trigger and ground electrode to find optimum conditions in order to produce high output energy.
3.1 Relation between capacitance and laser output energy
Laser output energy depends on the capacitance C that connected parallel with the discharge tube. Gas pressure, and distance between trigger and ground electrode were fixed to be 3.0 kPa and 1 cm respectively. In this experiment, capacitance of 570 pF, 700 pF, 900 pF, 1140 pF, 2000 pF and 2700 pF were used. The electrical energy was estimated by using the formula as shown below:

\[ E = \frac{1}{2} CV^2 \]  

Figure 3 shows dependence of laser energy on electrical energy. Laser energy increases with increasing in electrical energy for both laser tube in 40 cm and 30 cm length. Laser energy with discharge length 40 cm is higher than 30 cm because the high energy was applied. However, for discharge length of 40 cm, laser energy decreases as the electrical energy is more than 400 mJ. When the electrical energy is getting higher, laser oscillation become unstable due to residual charge.

![Figure 3. Dependence of the laser output energy on electrical energy](image1.jpg)

3.2 Relation between pressure and laser output energy
Figure 4 shows the dependence of the laser output energy on gas pressure for 40 cm discharge length. In this case, capacitance C, and distance between trigger and ground electrode were fixed to be 700 pF and 1 cm, respectively. Results shown in Fig. 4 indicates that laser output energy as a function of gas pressure various changing voltage. Optimum gas pressure for laser with discharge length of 40 cm depends on the charging voltage.

![Figure 4. Dependence of the laser output energy on CO₂ gas pressure for different charging voltage](image2.jpg)

When the gas was supplied at low pressure, the laser output energy become low due to low gas density. Laser output energy have a peak value at gas pressure around 3.0 kPa when 20 kV is being
applied, as shown in Fig. 4. Laser energy decreases as the gas pressure flowed more than 3.5 kPa. At 20 kV charging voltage, when the gas pressure is set more than 3.5 kPa, laser energy decreases due to high discharge impedance caused by high gas density. Therefore, the optimization of pressure and charging voltage are required to produce high output energy.

3.3 Relation between capacitance between trigger and ground electrode $C_d$ and laser output energy

In this experiment, 40 cm of discharge length was used. The charging voltage, capacitance $C$, and gas pressure were fixed to be 20 kV, 700 pF and 3 kPa, respectively, to examine laser energy dependence on capacitance between trigger and ground electrode.

To calculate the capacitance between trigger and ground electrode, assuming that $C_1$ and $C_2$ were connected in parallel as shown in Fig. 5. The total of capacitance between trigger and ground electrode $C_d$ is equal to the sum of $C_1$ and $C_2$. Therefore,

$$C_d = \epsilon_0 \frac{a}{d} S_A + \epsilon_0 \frac{b}{d} S_c$$

where,

- $a$: inner diameter of laser tube
- $b$: outer diameter of laser tube
- $c$: outer diameter of copper sheet
- $d$: distance between trigger and ground electrode
- $S_A, S_B$: cross-sectional area of laser tube
- $S_c, S_D$: cross-sectional area of copper sheet
- $\epsilon_0$: permittivity of free space
- $\epsilon_r$: relative permittivity

Distance between trigger and ground electrode which are 0.5 cm, 1.0 cm, 1.5 cm and 2.0 cm correspond to the 0.65 pF, 0.32 pF, 0.22 pF and 0.16 pF, of capacitances, respectively. As shown in Fig. 6, laser oscillates when the distance between trigger and ground electrode is within 0.5 cm to 2 cm. When the distance is set more than 2 cm (trigger capacitance less than 0.16 pF), the laser oscillation did not occur. As the distance between trigger electrode and ground electrode increases, the charge is not satisfied to trigger the discharge. Hence, optimum trigger capacitance is existed for this laser scheme.
Figure 6. Dependence of laser output energy on capacitance between trigger and ground electrode

4. Conclusion
Simple, compact and affordable longitudinally excited CO₂ laser controlled by fast high voltage solid state switch has been developed. In conclusion, longer discharge length and high voltage produce stable and high power of laser oscillation. Additionally, this laser scheme can successfully make an oscillation at several conditions that optimum electric charge, gas pressure, and capacitance between trigger and electrode. There are various factors that influence the performance of longitudinally excited CO₂ laser need to be concern.

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