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Technical Communication

Simple and Compact Longitudinally Excited CO_2 Laser Driven with A Fast High-Voltage Solid-State Switch

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A simple and flexible method to realize a discharge-pumped CO_2 laser using a fast high-voltage solid-state switch is presented. A longitudinal excitation scheme that implements this simple configuration has been adapted. A fast high-voltage solid-state switch consisting of an avalanche transistor and commercially available series-connected IGBTs is coupled with a compact laser tube filled with CO_2 gas to provide the excitation energy. Laser oscillation has been demonstrated successfully and has produced several millijoules of output energy.

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1. Introduction

A CO_2 laser is a gas laser that produces a strong infrared light at wavelengths ranging from 9.4 μm to 11.6 μm. The excitation schemes used for a CO_2 laser are classified into longitudinal and transverse excitation schemes according to the structure of the discharge tube.

The pulsed CO_2 laser, such as a transversely excited atmospheric (TEA) CO_2 laser, has received attention because of its successful applications. In general, a TEA CO_2 laser emits pulses with a high output energy and a short pulse width (typically a spike pulse with a pulse width of approximately 100 ns and a pulse tail of several microseconds). The TEA CO_2 laser is used in various applications, including laser ablation in material processing, medical surgery, light detection and ranging (LIDAR), and surface cleaning [1-4]. However, due to the complexity, high cost, and ongoing maintenance requirements, TEA CO_2 lasers have presented significant challenges for many users, and their applications are limited for huge companies or businesses because of the high investment needed. Therefore, there is demand for a simple, compact, maintenance-free, and affordable pulsed CO_2 laser.

Recently, Uno et al. has reported that, longitudinally excited CO_2 laser with the aid of a fast discharge circuit produces a short laser pulse, like the TEA CO_2 laser [5]. An output energy of 50 mJ with a pulse width of approximately 100 ns and a pulse tail length of 60 μs has been easily achieved [6]. In the longitudinal excitation scheme, the discharge is produced along the direction of the laser axis, and the electrodes are well separated, resulting in a small discharge cross-section. The long discharge length provides a high breakdown voltage at a low gas pressure. Laser oscillation at low gas pressure can be realized by the uniform discharge due to the fast electron drift velocity. In addition, the discharge uniformity is not affected by the residual charge because a diffused streamer discharge takes place in a discharge tube. This scheme does not require a preionization system or a fast gas flow system [5-13]. Since the longitudinal excitation scheme has essential advantages of lower cost and greater compactness than the transverse excitation scheme, a simple, compact, and affordable pulsed gas laser can be realized.

A discharge switch is the most important part in the discharge-pumped pulsed laser in order to rapidly switch out the high-voltage pulse for efficient pumping. A high-voltage switch, such as a spark gap or a thyratron, has usually been used with a TEA CO_2 laser to generate a short pulsed discharge. A spark gap switch is a simple and low-cost device that consists of two conducting electrodes separated by a gap usually filled with a gas such as nitrogen. This device is designed to allow an electric spark to pass between the conductors [14]. Uno et al. used a spark gap switch capable of switching out of high voltage with a fast rise time of less than 100 ns for operation of a longitudinally excited gas laser [6]. However, the spark gap switch is operated in the arc mode and suffers from the recovery problem, causing a short service life and low efficiency for high-repetition operation. In addition, electrode corrosion is the most common form of damage in the spark gap switch caused by repeated heavy discharge. Like a spark gap switch, the thyratron is also a gas-filled switch. The thyratron has high performance when performing highly repetitive operation because of its faster deionization time. However, the thyratron is expensive and has a limited service time due to electrode erosion and fill gas degradation. Neither switch can currently meet the demand for industrial mass production by TEA CO_2 laser.

Current fabrication technology for high-power semiconductors easily makes devices with high breakdown voltage, high current handling, high efficiency in highly repetitive operation, and fast switching times. The solid-state switch presents significant advantages compared to the spark gap and thyratron, such as stability for high-repetition operation. As a result of recent technological advances in semiconductor power devices, the solid-state switch has been applied to gas laser excitation and plasma generation [15]. However, a commercially available solid-state switch having the capability of driving a high voltage and a large current is a high-cost product. This high cost prohibits progress in pulsed CO_2 lasers for manufacturing companies, particularly small and medium-sized companies. Therefore, affordable and flexible fast high-voltage solid-state switches (FHVSSs) are required for pulsed gas lasers. In other words, the combination of a longitudinally excited laser and an FHVSS is a promising approach for realizing industrial mass production using pulsed CO_2 lasers.

In the present paper, a simple and flexible method to realize a pulsed CO_2 laser driven by a laboratory-developed FHVSS is presented. The longitudinal excitation scheme has been selected for consideration in the present study. An FHVSS consisting of a single gate circuit and series-connected IGBTs is capable of replacing spark gap switches and thyratrons. Laser oscillation has been successfully demonstrated using an FHVSS at 10.6 μm. A simple, compact, and affordable pulsed CO_2 laser has been created, and the characteristics of an FHVSS and laser radiation are described.

2. Experimental

2.1. Fast high-voltage solid-state switch

Insulated-gate bipolar transistors are widely used in high-voltage and high-current applications due to their high voltage and current rating and low conduction loss. A commercially available discrete IGBT, IRG7PH42UD (1200 V, 45 A) [16], with an input capacitance of approximately 3,338 pF has been selected because this IGBT is inexpensive and readily available on the Internet for approximately \$10. In order to realize a solid-state switch with a high working voltage, several IGBTs are connected in series. For fast IGBT switching, it is necessary to drive the input capacitance by a pulse with a fast rise time. Therefore, construction of the gate drive circuit is important. Due to the demand for physically small circuits with low cost, the method reported by Baker et al. [17], which involves the connection of an avalanche transistor circuit to a MOSFET gate, has been applied in order to achieve fast switching of an IGBT.

An FHVSS that consists of an avalanche transistor circuit and series-connected IGBTs has been developed. Figure 1 shows a schematic diagram of an FHVSS for operation at the high voltage required for a longitudinally discharge-pumped CO_2 laser. The proposed scheme offers a simple topology of an electric circuit. In Fig. 1, T, *C*, and *V* denote the IGBT, the capacitor, and the DC supply, respectively. In the FHVSS, the avalanche transistor circuit is connected to the IGBT gate (T_1) to provide a pulse with a fast rise time, which contributes to rapid charging of the input capacitance of the IGBT for fast switching. The avalanche transistor 2N5551 was selected because it is inexpensive and readily available. The avalanche effect in 2N5551 is usually generated at a reverse voltage V_a of 280 V or greater, then the 2N5551 turns on at a switching time of 5 ns or less.

The basic theory of multistage switching of the FHVSS, which is unique and novel as far as we know, is explained as follows. The DC voltage V_c is applied between the collector of T_5 and the ground. At the same time, all the gate capacitors (C_1–C_4) connected to the gate of each IGBT and the emitters of lower-stage IGBTs are charged. When a V_a exceeding 280 V is applied to the avalanche transistor circuit, the 2N5551 is operated in the avalanche mode and is turned on in several nanoseconds. The voltage pulse with a rise time of nanoseconds produced by the avalanche transistor quickly charges the input capacitance of T_1, and then T_1 turns on rapidly. When T_1 turns on, a voltage potential is generated between the gate and the emitter of T_2 in the second stage. At that moment, when the terminal voltage of C_1 is sufficiently high to drive the gate of T_2, T_2 is turned on due to the discharge of C_1. Repeating this process allows for the successive activation of IGBTs from T_3 to T_5. This circuit is compact and affordable because a gate drive circuit is not required for each IGBT, and an inexpensive IGBT is used.

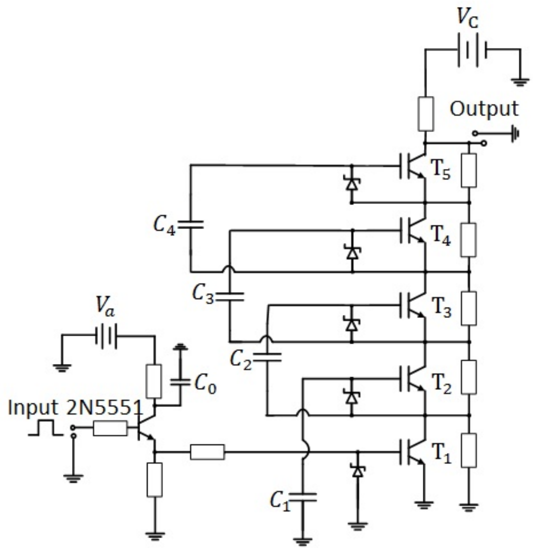

Fig. 1 Schematic diagram of a fast high-voltage solid-state switch

In the FHVSS, the consideration of the amount of capacitance C_0 that is connected to the collector of the avalanche transistor is necessary. Here, C_0 must be large enough to supply the amount of charge needed to turn on T_1. The value of C_0 was experimentally set to be 680 pF. Moreover, the gate capacitors (C_1–C_4) are important in multistage switching. The amount of gate capacitor is determined by the voltage across the gate terminal of each IGBT. As the stage level increases, the voltage across the gate terminal of the IGBT (T_2–T_5) becomes higher. In this regard, the amount of gate capacitance required for turning on IGBTs T_2 to T_5 is becoming smaller. Thus, selecting an appropriate capacitance is advantageous for achieving a faster switching time. The capacitances of C_1, C_2, C_3, and C_4 were experimentally determined to be 220 pF, 167 pF, 130 pF, and 100 pF, respectively, for a V_c of 7 kV. A resistance of 2 MΩ was connected in parallel to the collector-emitter of each IGBT in order to allow equal biasing at all stages. In addition, a Zener diode (RD30EB) having a Zener voltage of 30 V was connected between the gate and the emitter of each IGBT in order to protect the gate from excessive voltage. The FHVSS was made on a double-sided Teflon printed circuit board, which is suitable for high-frequency and high-voltage applications.

2.2. Longitudinally excited CO_2 laser with an FHVSS

The longitudinally excited CO_2 laser consists of a DC power supply, a resistor, a capacitor, a laser tube consisting of a discharge tube and resonator mirrors, and an FHVSS, as shown in Fig. 2. The discharge tube of a 20-cm-long ceramic tube with inner and outer diameters of 13 mm and 17 mm, respectively, is used. Two metallic electrodes are attached to both ends of the discharge tube. A totally reflective spherical mirror with a radius of curvature of 20 m and a flat output mirror with a reflectivity of 80% are also attached to both ends of the discharge tube, forming a resonator. The distance between the mirrors (i.e., the cavity length) is 27 cm. A mixed (CO_2:N_2:He = 1:1:2) gas is fed into one end of the laser tube at a pressure of a few kilo Pascal and pumped out the gas through the other end of the laser tube by using a rotary pump.

A capacitor C_L connected in series with the laser tube is charged by the current that flows from the DC power supply. The DC power supply also charges the capacitors (C_1–C_4) in the FHVSS. When the FHVSS is rapidly switched out, the charge stored in C_L is quickly discharged, and then the voltage difference between the laser tube and the ground is generated. Rapid discharge takes place in the laser tube, and then laser oscillation should occur.

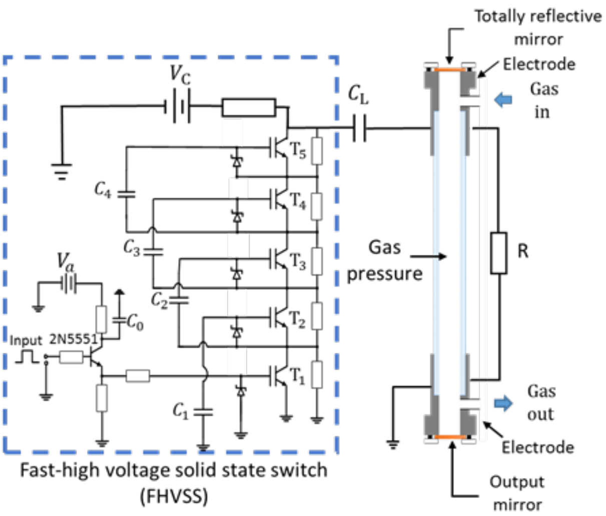

Fig. 2 Schematic diagram of a longitudinally excited CO_2 laser driven by a fast high-voltage solid-state switch

3. Results and Discussions

3.1. Fast high-voltage solid-state switch using IGBT

Figure 3 shows the switching characteristic of an FHVSS measured at the collector of T5 using a high-voltage probe (Tektronix P6015A) having a frequency response of 75 MHz. The switching time is evaluated for 10-90% of the output waveform. A high voltage of approximately 7 kV was successfully switched out by the developed FHVSS for a rise time of 12 ns. According to the specifications listed in the datasheet of the IGBT, the rise time of the IGBT used in the present study is 32 ns in standard operation [16]. By using an avalanche transistor for the gate drive circuit, fast switching has been achieved despite the series-connected operation. Since the spark gap switch is usually operated at a switching time of several tens of nanoseconds at a high voltage of approximately 10 kV, the FHVSS can be implemented in the discharge-pumped laser to replace the spark gap switch and functioned as a discharge switch to provide stable laser oscillation. The allowable operating voltage for the switching can be simply increased by increasing the number of IGBTs in a series connection depending upon the desired working voltage. In addition, this FHVSS is compact and affordable because a gate drive circuit is not required for each IGBT and inexpensive IGBTs are used.

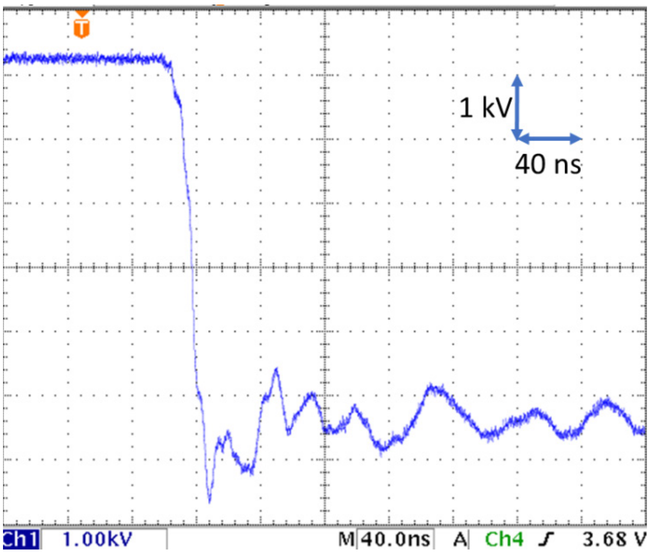

Fig. 3 Switching waveform of the FHVSS at 7 kV DC

3.2. Laser characteristics of a longitudinally excited CO_2 laser with an FHVSS

Laser oscillation was successfully demonstrated when a DC voltage exceeding 7 kV was applied to the laser tube. The laser energy dependence on the gas pressure and the electrical energy stored in C_L are examined. The laser output energy was measured with an energy detector (Gentex ED-200). Figure 4 shows the dependence of laser output energy on gas pressure. In this case, C_L was fixed to be 2,000 pF. The laser output energy reaches a maximum value of 3 mJ at a gas pressure of approximately 1.3 kPa. When the gas pressure flow inside the discharge tube is low, the laser output energy decreases due to low gas density. When the gas pressure is more than 1.3 kPa, the laser output energy decreases due to the high discharge impedance caused by high gas density.

Figure 5 shows the dependence of the laser output energy on the electrical energy. The gas pressure was fixed to be 1.3 kPa in this experiment. The horizontal axis, which shows the electrical energy stored in the C_L, was calculated as $CV^2/2$, where C and V are the capacitance and applied voltage, respectively. The obtained results indicate that laser energy increases with increasing electrical energy. The energy efficiency was estimated to be 12.5% based on the fitting line to the data shown in Fig. 5.

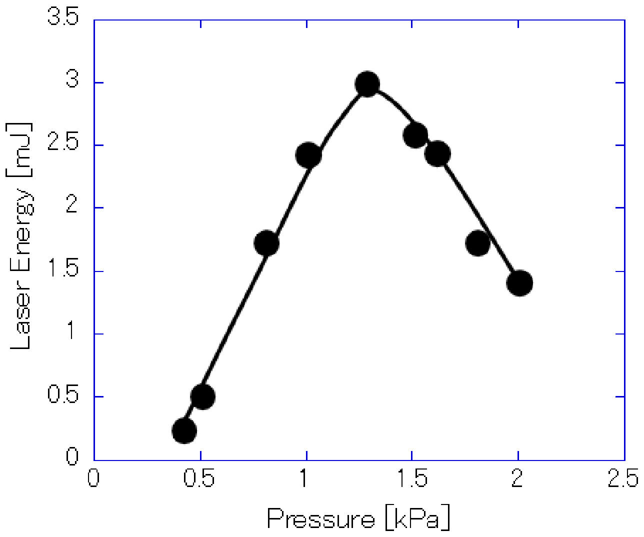

Fig. 4 Dependence of laser output energy on gas pressure

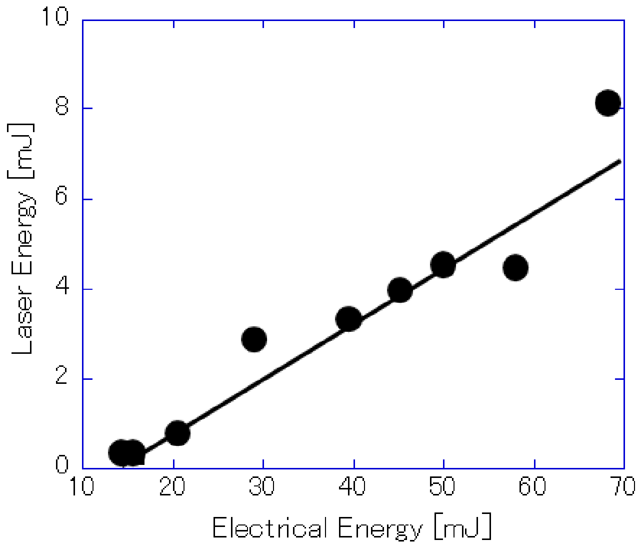

Fig. 5 Dependence of laser output energy on electrical energy

Laser oscillation has been achieved successfully, and the highest laser energy is obtained at a gas pressure of approximately 1.3 kPa at a DC voltage of 7 kV. The longitudinal excitation scheme does not require a fast gas flow system, which makes the body compact and decreases the installation area. The laser output energy depends on the discharge volume and the input energy in the present scheme. Future study is needed in order to improve the laser performance so that the laser can produce a higher output energy that is suitable for material processing in medical and industrial applications. For instance, higher laser energy can be easily achieved by increasing the length of the discharge tube and providing a greater input energy. An FHVSS has great flexibility for increasing the drive voltage in principle [18]. Greater input energy, however, can cause higher running costs and shorten the lifetime of the laser. Note that the efficiency of the pulsed power supply also affects the quality and performance of the laser. Therefore, optimization of the relation between the discharge length or volume and the suitable conditions of the FHVSS must be clarified.

4. Conclusions

In the present study, we have proposed and demonstrated a simple and flexible method for realizing a longitudinally excited CO_2 laser with an FHVSS. In the future, the well-designed combination of an FHVSS and a longitudinally excitation scheme that offers simple construction, great compactness, high cost-effectiveness, and high energy efficiency is expected to have superior properties for industrial applications.

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