KIEE International Transactions on EA, Vol. 3-C, No. 4, pp. 123~129, 2003 **123**

A CW CO_2 Laser Using a High Voltage Dc-dc Converter with Half-bridge Resonant Inverter and Cockroft-Walton Multiplier

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Abstract - We propose a high voltage dc-dc converter for a CW (continuous wave) CO_2 laser system using a current resonant half-bridge inverter and a Cockcroft-Walton circuit. This high voltage power supply includes a 2-stage voltage multiplier driven by a regulated half-bridge series resonant inverter. The inverter drives a step-up transformer and the secondary transformer is applied to the voltage multiplier. It is highly efficient because of the reduced amount of switching losses by virtue of the current resonant half-bridge inverter, and also due to the small size, low parasitic capacitance in the transformer stage owing to the low number of winding turns of the step up secondary transformer combined with the Cockroft-Walton circuit. We obtained a maximum laser output power of 44 W and a maximum system efficiency of over 16%.

Keywords: CO_2 laser, Dc-dc converter, ZCS half-bridge inverter, Cockroft-Walton circuit.

1. Introduction

At the present time, CO_2 lasers are widely used in a variety of fields including materials fabrication, industrial instrumentation, medical equipment, remote sensing and for military purposes. It is important to exert precise control of the laser output power in these applications [1-3].

The conventional CO_2 laser power supplies have been designed for constant voltage or power applications so that they are unable to perform well under the wide range of load conditions. Moreover, in these supplies, the circuit elements such as high voltage transformers, high voltage switches and energy storage capacitors are necessary, and the secondary transformer is connected to a rectifier and a filter capacitor. Consequently, those supplies are expensive and require a large space.

In this study, we introduce a high voltage dc-dc converter using a half-bridge ZCS (Zero Current Switching) resonant inverter and Cockroft-Walton voltage multiplier as the pumping source of the gas mixture, which could be applied to a low-power CO_2 laser below 100W.

This high voltage power supply includes a 2-stage voltage multiplier driven by a regulated half-bridge series resonant inverter operating below resonance. The inverter drives the step up transformer (1:17). The secondary transformer is applied to the voltage multiplier.

These proposed techniques have several advantages. First, this combination guarantees small parasitic capacitance in the transformer stage, as well as rapid dynamic response and small size because of the low winding-turn number of the secondary transformer. Second, system efficiency is high because the ZCS resonant inverter creates fewer switching losses. Third, it is very easy to control laser output energy by adjusting the operating frequency of the half-bridge inverter using a PIC (Programmable Integrated Controller) microprocessor. Thus, this power supply is very useful in high voltage areas of over 15kV.

In order to investigate the operational characteristics of this CO_2 laser system, experiments have been carried out as a function of the capacitance value of the blocking capacitor, total input energy, switching frequency, and the capacitance of capacitors in the Cockcroft-Walton circuit. A laser discharge tube was fabricated as an axial and water cooled type.

2. Design

2.1 Laser Resonator

The type of laser that we investigated is used for sealed water-cooled devices made of pyrex. The experiment is equipped with a plano-concave resonator. The optical resonator is formed by a totally reflecting Mo mirror with 10m radius of curvature and a 90% reflecting ZnSe flat output coupler separated by 100cm. The discharge length is about 90cm. The construction of a hollow cylinder for an aluminum cathode is employed to minimize sputtering. The laser tube is considered to be a lower pressure than 20 torr and the gas mixture of $CO_2/N_2/He=1/3/10$ optimized to

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Received March 5, 2003 ; Accepted September 15, 2003

yield maximum power is used in the experiment.

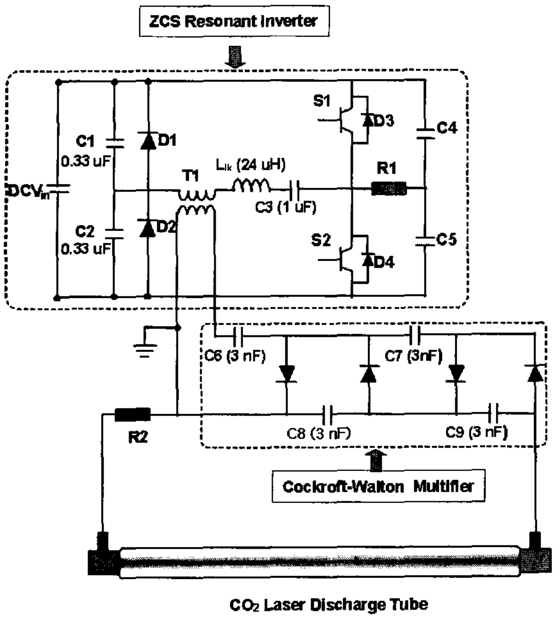


Fig. 1 Dc-dc converter for CW CO_2 laser using resonant inverter and Cockroft-Walton multiplier.

2.2 High Voltage Power Circuit

It is necessary for high voltages over 15kV to ignite electric discharge in a tube with the pressure of 18 torr and the discharge length of 90cm between two electrodes.

Fig. 1 shows a high voltage Dc-dc converter used for the CW CO_2 laser. The circuit consists of a high power resonant inverter in half-bridge configuration, a high frequency step-up transformer and a high voltage multiplier using a Cockroft-Walton circuit.

The high voltage asymmetrical cascade rectifier was made to our specifications. The high voltage supply includes a 2 stage voltage multiplier driven by a regulated half-bridge inverter operating below resonance. The inverter drives the step up transformer and the secondary transformer is applied to a voltage multiplier. This combination guarantees small parasitic capacitance in the transformer stage and swift dynamic response. In particular, the ZCS series resonant inverter was used to decrease the loss by the tailing current generated on turning off an IGBT (Insulated gate bipolar transistor) [4-5].

The ZCS series resonant inverter consists of two IGBTs (S1, S2), a leakage inductor (L_{lk}), a blocking capacitor (C3), and charging capacitors (C1, C2). The switching loss is zero in principle, which is adequate in high repetition rate operation because the current through S1, S2, C1, and C2 is forced to the sinusoidal wave, and the switch devices are turned on/off at zero current. The output of the ZCS series resonant inverter is:

$$P_{out} = 2fCV^2_{in}$$

where f is the operating frequency, C the capacitance of the charging capacitor, and DCV_{in} the input voltage. According to this formula, it is found that there are two ways to control the power density of the resonant inverter. One is to vary the input voltage DCV_{in} at a constant pulse width and the other is to adjust the switching frequency f [6].

The proposed ZCS inverter equivalent circuit and operating modes are shown in Fig. 2. The switching IGBT S1 and S2 form only one side of the bridge-connected circuit, the remaining half being formed by the C1 and C2 capacitors. The diodes (D3, D4) that are connected in antiparallel to the IGBTs are called freewheeling diodes. These diodes are able to provide a path for the resonant current in the direction opposite to the current direction in the IGBTs when the corresponding switch around which it is connected is in the off position. This is particularly important because the load is reactive.

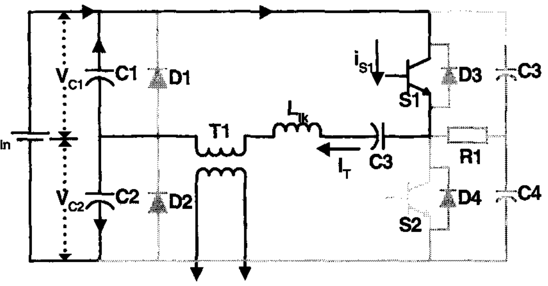
Components C4, C5 and R1 are often referred to as snubber components; they assist the turn-off action of the high-voltage IGBT S1 and S2 so as to reduce secondary breakdown stress. As the IGBTs turn off, the transformer inductance maintains a current flow, and the snubber components provide an alternative path for this current, preventing excessive voltage stress during the turn-off action.

The inverter switches may be in one of three different configurations at any given time; 1) S1 may be closed (on) while S2 is open (off), 2) S1 may be open while S2 is closed, or 3) both switches may be open.

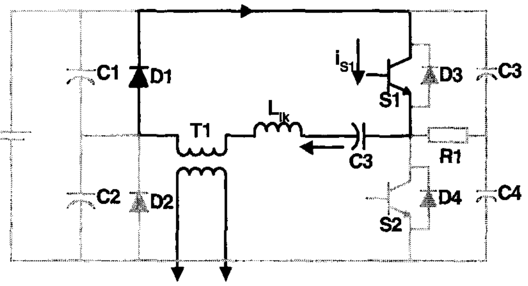
Since C1 and C2 are the charging capacitors, they have a small capacitance. Before the power supply operates, capacitors C1 and C2 are initially equally charged so that the voltage at the center point, node A, will be half the supply voltage DCV_{in}. However, under steady-state conditions, the voltage at the center point of C1 and C2 will change significantly during a cycle of operating even though the value of the voltage sum of the two capacitors is equal to that of input voltage DCV_{in}.

The circuit operation can be divided into three modes under steady state.

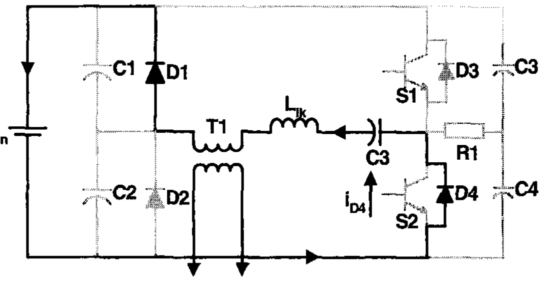
Mode 1($t_0 \leq t < t_1$): The equivalent circuits are shown in Fig. 2(a). When the top IGBT S1 turns on at time t_0, a voltage of C1 will be applied across the primary winding of step-up transformer T1 with the start going positive. The resonant current I_T flows through the path C1→S1→C3→L_{lk}→T1→C1 and the path DCV_{in}→S1→C3→L_{lk}→T1→C2. This process charges C2 during C1 discharge to the load. As a result of that, the value of the charging capacitor voltage V_{C1} becomes zero with discharging and that of V_{C2} becomes that of input voltage DCV_{in} with charging as can be seen in Fig. 3.



(a) Mode 1 : $t_0 < t < t_1$



(b) Mode 2 : $t_1 < t < t_2$



(C) Mode 3 : $t_2 < t < t_3$

Fig. 2 Equivalent circuits of operation modes for the ZCS resonant inverter divided into three modes.

Mode 2($t_1 \le t < t_2$): The current through a leakage inductor L_{lk} begins to flow through C3→L_{lk}→T1 →D1→ S1→ C3 at t_1 as can be seen in Fig. 2(b). A reflected load current and magnetization current will now build up in the transformer primary and Sl. After the time defined by the control circuit, S1 will be turned off at t_2.

Mode 3($t_2 \le t < t_3$): The equivalent circuit is shown in Fig. 2(c). Even though the IGBT S1 is turned off at time t_2, as a result of the primary leakage inductance, resonant current will continue to flow into the start of the primary winding through C3→L_{lk}→T1→D1→DCV_{in}→D4→C3. If the energy stored in the primary leakage inductance is sufficiently large, diode D4 will eventually be brought into conduction to clamp any further negative excursion and return the remaining flyback energy to the supply.

After a period defined by the control circuit, S2 will also turn on, taking the start of the primary winding negative. Load and magnetizing currents will now flow in S2 and into the transformer primary winding finish so that the former process will repeat, but with primary current in the opposite direction. The difference is that at the end of an "on" period D3 is brought into conduction, returning the leakage inductance energy to the supply line (DCV_{in}). The value of V_{C1} becomes that of DCV_{in} and that of V_{C2} will be zero with being discharged to load after S2 turns off. Fig. 3 shows the voltages of the charging capacitors (C1, .C2), resonant current (i_T), and current through diode (D1) during a switching cycle (S1: turn on, S2: turn off).

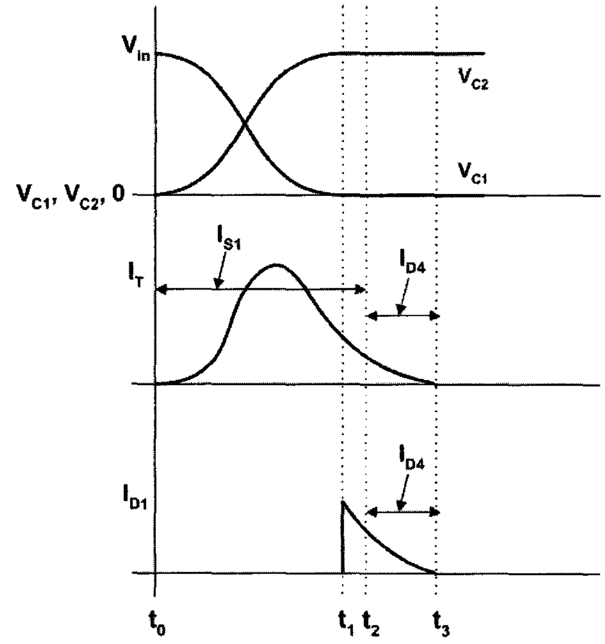


Fig. 3 Voltage of charging capacitors (C1, C2), resonant current (i_T), and current through diode (D1) during a switching cycle

The transformer used in this circuit is wound on a flyback ferrite core (FUR5177S) constructed by Samhwa electronics Inc, Korea. The secondary is wound on top of the primary with a layer of Teflon tape between the two windings for insulation. Litz wire was used for firm coupling and the primary was rounded to the nearest lower turn. The primary voltage of the transformer is calculated considering voltage drops. The secondary transformer voltage can be derived considering diode drops, and other loss factors. As a result, the turn ratio of the transformer is determined to be 1:17. The primary winding turns is 40 turns and the secondary winding turns is 700 turns.

A 2 stage Cockcroft-Walton voltage multiplier serves as a high voltage generator to carry out the glow discharge in this laser tube. A simplified analysis of the cascade rectifier operation, constructed in an asymmetrical fashion, shows that energy is transferred from the source (step-up transformer) to C6 (Fig. 1), which transfers it to C8 and so forth. An n-stage cascade rectifier can provide a dc output voltage of magnitude $2nV_P$ under no-load conditions (V_P is the peak value of the ac power source). Laser tube can be considered as a resistive load during a glow-discharge process. Thus, the average output voltage will be smaller than the value $2nV_P$ due to a load current dependent voltage drop. A 2-stage cascade rectifier, in this circuit, can provide a dc output voltage of more than 15kV under no load conditions and an input voltage of 230V because the peak voltage value from the step-up pulse transformer is about 4kV [7, 8].

In the Cockroft-Walton circuit, the capacitance of C6~C9 is 3 nF and the diodes are RVT1500 (fast recovery diodes).

3. Experimental Result

In order to verify the theoretical analysis and the operational principle of the Dc-dc converter as related to laser performance, a ZCS Dc-dc converter using a ZCS resonant inverter and a Cockroft-Walton circuit has been manufactured and tested in the laboratory. This power supply works in an operating frequency of 8.3 ㎑.

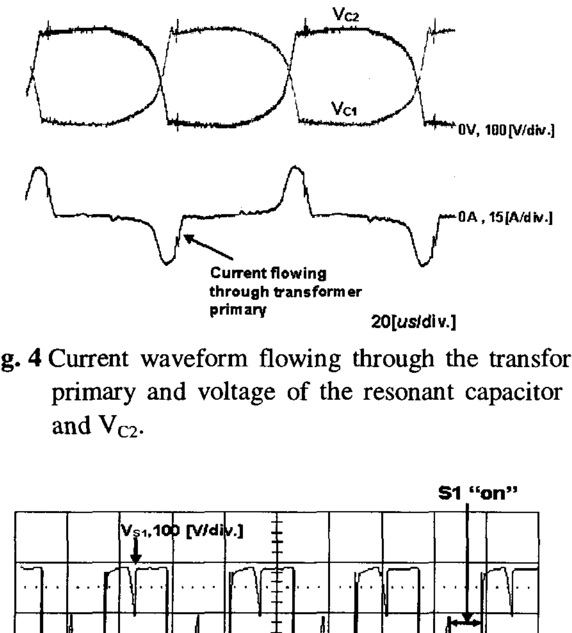


Fig. 4 Current waveform flowing through the transformer primary and voltage of the resonant capacitor V_{C1} and V_{C2}.

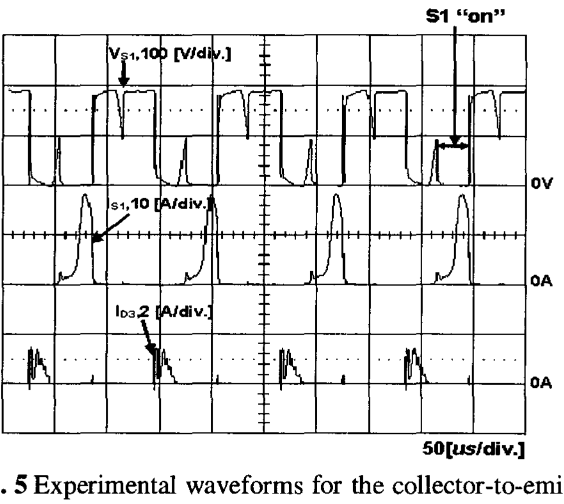


Fig. 5 Experimental waveforms for the collector-to-emitter voltage, current of S1 with their current and bypass current flowing through diode D4.

Fig. 4 shows the current flowing through the primary of the transformer and the voltage of the charging capacitor. Fig. 5 depicts the experimental waveform for the collector-to-emitter voltage, current of the IGBT S1 and also the bypass current flowing through the freewheeling diode D_4 when S2 is turned off. Fig. 6 illustrates a voltage waveform from the driving circuit used in turning on the IGBTs and the current waveform flowing through the primary of the transformer. The current waveform is similar to a sinusoidal wave and they can demonstrate ZCS operation. Thanks to this ZCS operation, switching losses are considerably relieved.

Fig. 7 shows the system start-up process at an operating frequency of 8.3 ㎑ and an input voltage of 230 V. The discharge firing voltage is approximately 15.8kV and the sustained voltage is roughly 10.2kV between electrodes in this laser tube. As can be seen in this picture, approximately 5.7 ms or 47.5 cycles are needed to reach the firing voltage.

Fig.s 8 & 9 illustrate collector-to-emitter current waveform and current stress of S1 as the capacitance of C3.

Fig. 10 shows the laser output power and the system output efficiency as the capacitance of C3 under total input power conditions, which is approximately 300W. Its laser output power was measured by using an energy meter (Gentec: PS-1K). The system output efficiency refers to the efficiency in converting input electrical energy into laser light. The laser output power falls by 24% from 42W to 32W with rising at the capacitance value and the efficiency also decreases by 2.2% from 13.7% to 11.5%. Fig.s 8 & 9 clearly show the effect of ZCS. In this Fig., the current stress increases from 6A to 16A, leading to a switching loss as the capacitance value of C3 increases. Therefore, the laser output efficiency diminishes as the capacitance of the blocking capacitor value increases. The switching stress is also essential from the viewpoint of conducted EMI (electromagnetic interference), because the application of the soft-switching technique can reduce not only switching losses but also lower the conducted EMI levels [9].

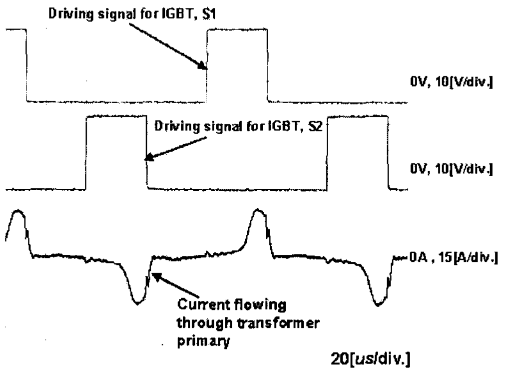


Fig. 6 IGBT driving signals and current waveform flowing through the transformer primary.

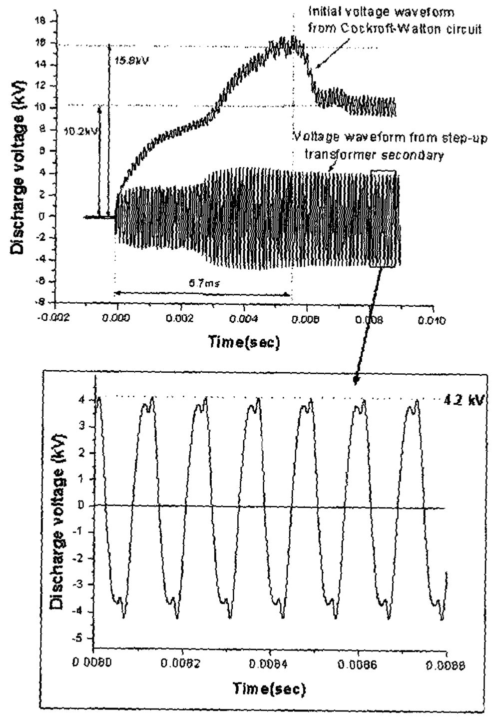


Fig. 7 Start-up transient process of Cockcroft-Walton circuit.

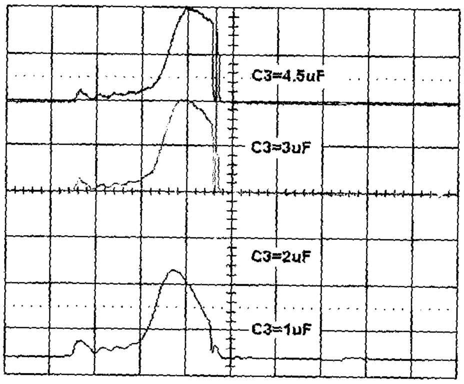


Fig. 8 Collector-to-emitter current waveform of S1 as the variation of blocking capacitor C3(Horizontal: 10 [*u*s/div], Vertical: 8[A/div]).

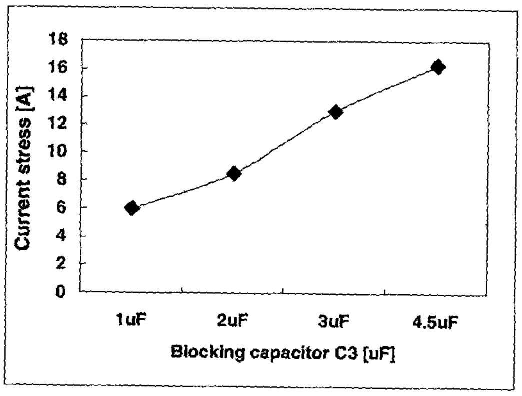


Fig. 9 Current stress of S1 as the variation of blocking capacitor C3.

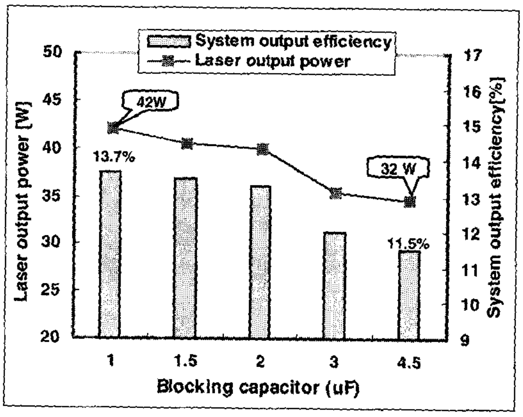


Fig. 10 Laser output characteristic as the value of a blocking capacitor (C3).

In Fig. 11, the laser output power and system output efficiency versus total input power are plotted for the blocking capacitor with a capability of 1uF. The laser output power increases to 44W with the rising input power, which is directly controlled by adjusting input voltage. However the laser output efficiency falls by about 4.9% from 16.2% to 11.3%. The discharge current increases with total input power because the sustained voltage of glow discharges is constant in the laser tube with a constant pressure in spite of the increasing input power. As the discharge current increases, the number of free electrons increases, which leads to an enforced electronic excitation of the upper laser level. If the current is too large, the power begins to saturate and diminish due to heating of the laser gas and saturation of the vibrational temperatures caused by depopulation processes [10].

In addition, it is known that the glow discharge becomes unstable and collapses into arc-like filaments or streamers when the input power is greater than a certain saturation value. This instability of the glow discharge is accompanied by a substantial drop in the electron energy, well below leV [11].

This is the temperature of the electron required to obtain high efficiency in transferring energy from the discharge to the upper vibrational levels of the CO_2 and N_2 molecules.

Fig. 12 shows the laser output power and efficiency obtained by varying the operating frequency at a fixed IGBT time of 30*u*s and an input voltage of 215V. As a result, the highest output of 37W was obtained at the operating frequency of 9.1 ㎑. Laser output power increases as frequency increases because the input power is proportional to the switching frequency but the system output efficiency is almost identical without regard to the operating frequency. This means that switching loss is very low. This circuit operates under resonance conditions with the result such that the rising rate of the total switching loss is minor even though the operating frequency increases.

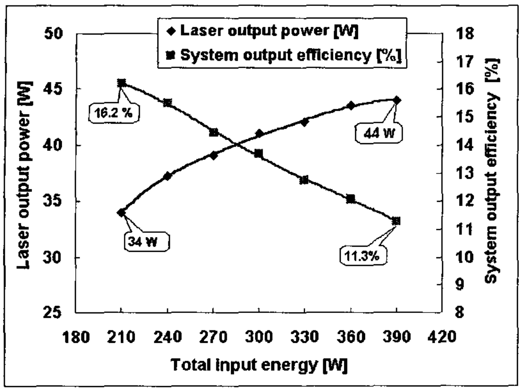


Fig. 11 Laser output power and efficiency as a function of input electrical energy for the blocking capacitance of 1uF.

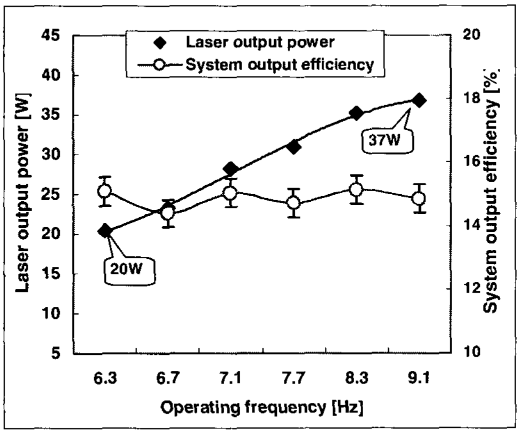


Fig. 12 Laser output power and efficiency as the operating frequency at a fixed IGBT time of 30*us* and an input voltage of 215V.

Fig. 13 shows an experimental waveform for the initial discharge voltage, that is the start-up transient process, as the capacitance of C8 and C9 in the Cockroft-Walton circuit. Fig. 14 shows the time lapse until firing voltage and voltage ripple rate initiate in C8 and C9.

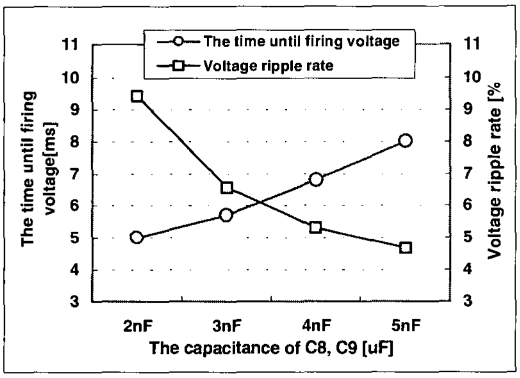


Fig. 13 Time lapse until the firing voltage and voltage ripple rate initiate as the capacitance of C8 & C9 in the Cockroft-Walton circuit.

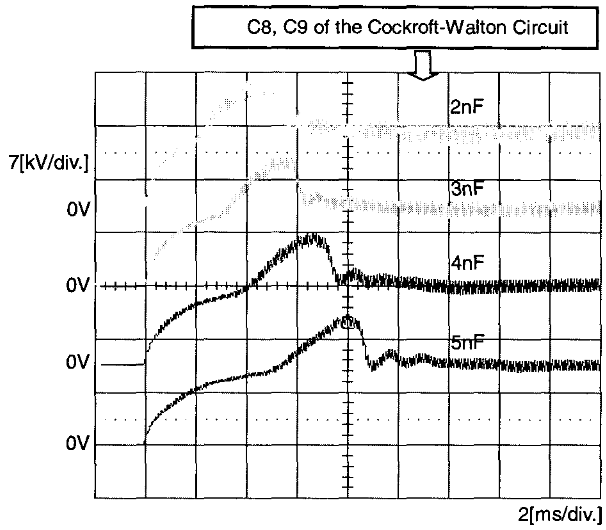


Fig. 14 Initial discharge voltage as the capacitance of C8, C9 in the Cockcroft-Walton circuit.

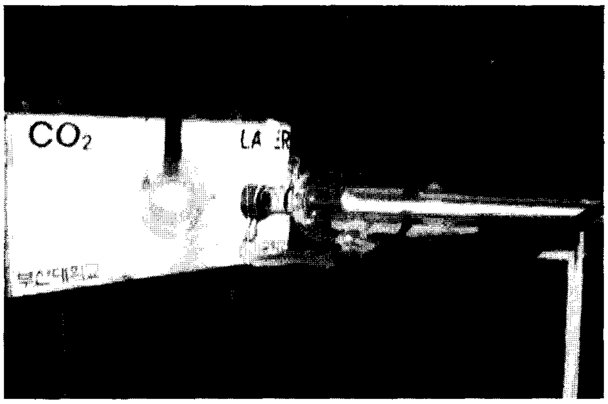


Fig. 15 Wood target being burned by CO_2 laser.

As can be seen in Fig. 14, additional time is required to reach discharge firing voltage by increasing the capacitance value of C8 and C9 in the Cockroft-Walton circuit, but the voltage ripple rate decreases. The voltage ripple rate is inversely proportional to the time taken to complete the start-up transient process.

Fig. 15 is a photograph of a wood target being burned by CO_2 laser.

5. Conclusion

In this study, we have proposed a CW CO_2 laser system adopting a Dc-dc converter with a current resonant half-bridge inverter and a Cockcroft-Walton circuit.

We have investigated operational characteristics of this CO_2 laser system as a function of the blocking capacitance, total input energy, operating frequency, and capacitance in the Cockcroft-Walton circuit.

The results indicate that it has high efficiency because of the reduction in switching losses by virtue of the current resonant half-bridge inverter, small parasitic capacitance in the transformer stage, rapid dynamic response and small size due to the low winding-turn of the step up secondary transformer used in conjunction with the Cockroft-Walton circuit.

We obtained a maximum laser output power of 44W and a system efficiency of over 11% at the input power condition of 390W. Furthermore, the maximum system efficiency was 16.2% at the input power condition of 210W and operating frequency of 8.3 ㎑.

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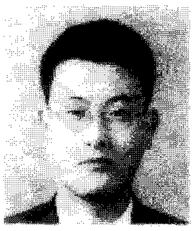

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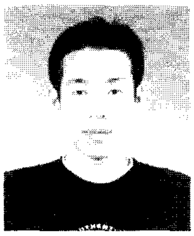

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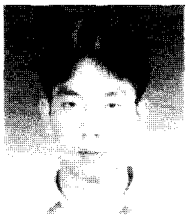

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