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A study on the efficiency improvement and miniaturization of a CW CO_2 laser using half-bridge resonant inverter and Cockroft-Walton multiplier

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Abstract - We propose a high voltage dc-dc converter for 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 transformer secondary is applied to the voltage multiplier. Thus, it has high efficiency because of the less switching losses by virtue of the current resonant half-bridge inverter, and also compact size, small parasitic capacitance in the transformer stage owing to the low number of a winding turn of the step up transformer secondary by combining with Cockroft-Walton circuit. We could be obtained the maximum laser output power of 44 W and the maximum system efficiency of over 16 %.

1. Introduction

We introduce a high voltage dc-dc converter using a half-bridge ZCS resonant inverter and Cockroft-Walton voltage multiplier for a 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 step up transformer. The transformer secondary is applied to the voltage multiplier.

This proposed techniques have several advantages. First, this combination guarantees small parasitic capacitance in the transformer stage, fast dynamic response and compact size because of a low winding-turn number of transformer secondary. Second, a system efficiency is high because ZCS(Zero Current Switching) resonant inverter provides less switching losses. Third, it is very easy to control laser output energy as adjusting the operating frequency of the half-bridge inverter by virtue of a PIC microprocessor.

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

2. Design

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

Figure 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 Cockroft-Walton circuit.

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, and it 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 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 two capacitors C1 and C2.

The diodes(D3, D4) that are connected in anti-parallel to the IGBTs are called freewheeling diodes. These diodes with IGBT 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 off. This is especially important because the load is reactive.

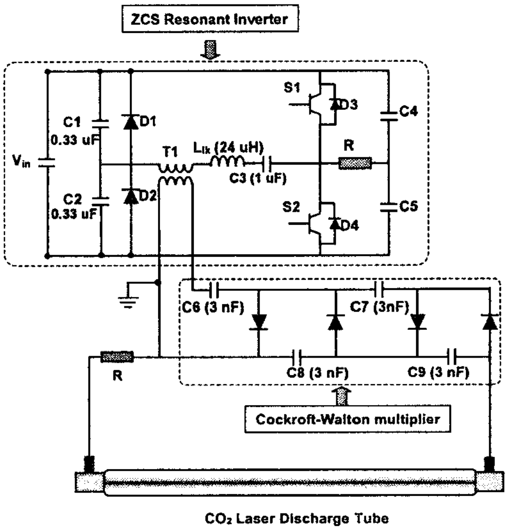

Fig. 1. DC-DC converter for CW CO_2 laser using resonant inverter and Cockroft-Walton multiplier

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

As C1 and C2 are the charging capacitors, they have a little small capacitance. Before the power supply operates, initially capacitors C1 and C2 equally charged so that the voltage at the center point, node

A, will be half the supply voltage V_{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 two capacitors is equal to that of input voltage V_{in}.

The circuit operation can be divided into three modes under steady state[1].

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 a 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 V_{in}→S1→C3→L_{lk}→T1→C2. This process charges C2 during C1 is discharged to 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 V_{in} with charging as can be seen in Fig. 3.

Mode 2($t_1 \leq t < t_2$) : Then 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 S1. After the time defined by the control circuit, S1 will be turned off at t_2.

Mode 3($t_2 \leq t < t_3$) : 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→V_{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 bringing D3 into conduction and returning the leakage inductance energy to the supply line(V_{in}). The value of V_{C1} becomes that of V_{in} and that of V_{C2} will be zero with being discharged to load after S2 turns off. Fig. 3 shows voltage of charging capacitors and resonant current of operation modes for the ZCS resonant inverter during a switching cycle.

The transformer used in this circuit is wound on a flyback ferrite core(FUR5177S). The turns ratio of the transformer is determined to be 1:17. The primary winding turns becomes 40 turns and the secondary one is 700 turns.

A 2 stage Cockcroft-Walton voltage multiplier serves as 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)[2-3].

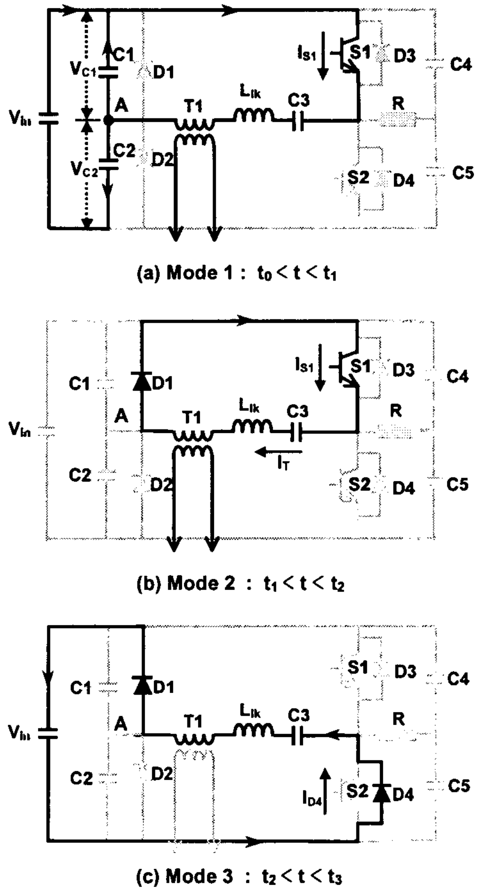

Fig. 2. Equivalent circuits of operation modes for the ZCS resonant inverter divided into three modes

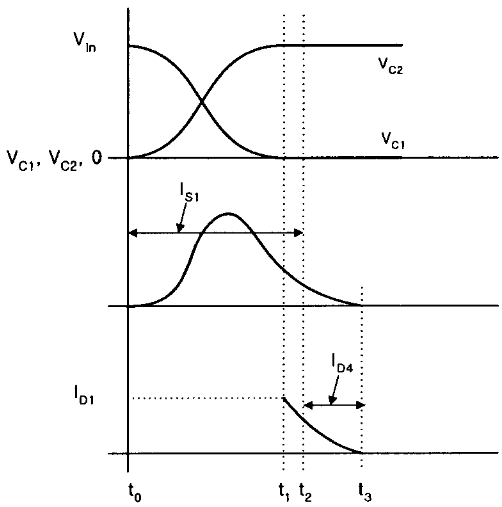

Fig. 3. Voltage of charging capacitors and resonant current of operation modes for the ZCS resonant converter during a switching cycle.

3. Experimental Results

Fig. 4 shows 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_3 when S2 is turned off.

Fig. 5 shows the system start-up process at a operating frequency of 8.3 ㎑ and a input voltage of 230 V. The discharge firing voltage is about 15.8 kV and the sustain voltage is approximately 10.2 kV between electrodes in this laser tube. As we can see in this picture, it needs approximately 5.7 ms, that is 47.5 cycles, to reach the firing voltage.

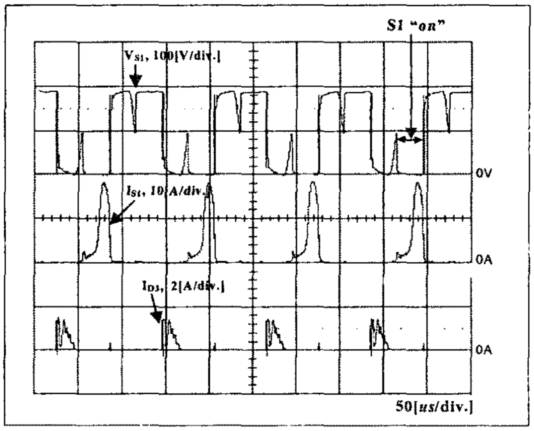

Fig. 4. Experimental waveforms for the collector-to-emitter voltage, current of S2 with their current and bypass current flowing through diode, D_4

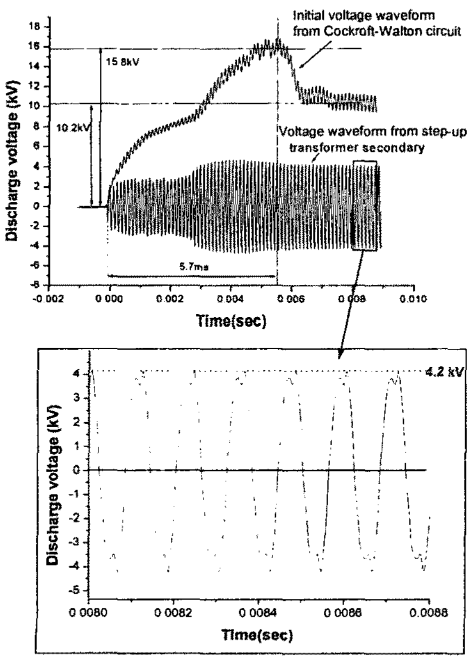

Fig. 5. Start-up transient process of Cockroft-Walton circuit

Fig. 6 shows the laser output power and efficiency obtained by varying the operating frequency at a fixed IGBT on time of 30us and an input voltage of 215 V. As a result, the highest output of 37 W was obtained at the operating frequency of 9.1 ㎑. Laser output power increases with increasing the frequency because the input power is proportional to the switching frequency but the system output efficiency is almost the same without regard to the operating frequency. It means that a switching loss is very low. This circuit operates under resonance condition with the result of that the rising rate of total switching loss is low even though the operating frequency increases.

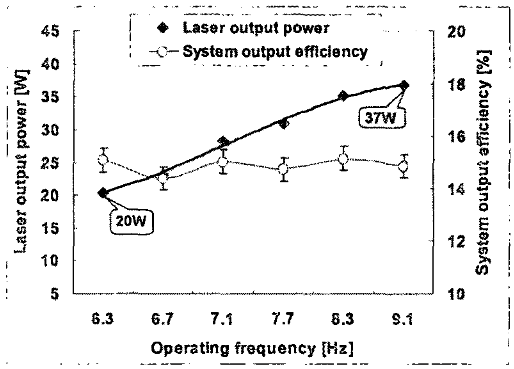

Fig. 6. The laser output power and efficiency as the operating frequency at a fixed IGBT on time of 30 us and an input voltage of 215 V.

4. Conclusions

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

As a result, it has high efficiency because of the less switching losses by virtue of the current resonant half-bridge inverter, and also small parasitic capacitance in the transformer stage, fast dynamic response and compact size because the winding-turn of step up transformer secondary is low by virtue of combining with cockroft-walton circuit.

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