A New CW CO₂ Laser with Precise Output and Minimal Fluctuation by Adopting a High-frequency LCC Resonant Converter

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Abstract – The current study proposes the design of a hybrid series-parallel resonant converter (SPRC) and a three-stage Cockcroft-Walton voltage multiplier for precisely adjusting the power generated by a continuous wave (CW) CO₂ laser. The design of a hybrid SPRC, called LCC resonant converter, is described, and the fundamental approximation of a high-voltage and high-frequency (HVHF) transformer with a resonant tank is discussed. The results of the current study show that the voltage drop and ripple of a three-stage Cockcroft-Walton voltage multiplier depend on frequency. The power generated by a CW CO₂ laser can be precisely adjusted by a variable-frequency controller using a DSP (TMS320F2812) microprocessor. The proposed LCC converter could be used to obtain a maximum laser output power of 23 W. Moreover, it could precisely adjust the laser output power within 4.3 to 23 W at an operating frequency range of 187.5 to 370 kHz. The maximum efficiency of the CO₂ laser system is approximately 16.5%, and the minimum ripple of output voltage is about 1.62%.

Keywords: LCC resonant converter, HVHF, Cockcroft-Walton

1. Introduction

Continuous wave (CW) CO₂ lasers have a wide range of applications in materials processing, such as in ablation and cutting, industrial instrumentation, the fabrication of medical equipment and for sealing of a dye-sensitized solar cells (DSSCs) [1]. In these fields, controlling the laser power and achieving a highly efficient power supply is important. Furthermore, being able to control the laser output power precisely is very important [1-7]. To achieve precise control of the power generated by a CO₂ laser, an RF CO₂ laser and a pinhole used for sealing of a DSSC are normally used [1, 8]. In the case of an RF CO₂ laser, the laser operating system is expensive and its structure is complex because it is composed of a π -matching circuit, RF generator, and so on. The DSSC-sealing method involving a pinhole results in heat loss because the laser output energy is absorbed by the pinhole.

Conventional CO₂ lasers have been designed to operate under a constant voltage and are, therefore, incapable of efficient power generation under varying load conditions. The design for a high-voltage DC-to-DC converter is problematic because the large transformer turns ratio exacerbates the transformer nonidealities. The conventional

power supply for CO₂ lasers is composed of a full-bridge circuit with elements such as a high-voltage and high-frequency (HVHF) transformer, a high-voltage capacitor, an expensive insulated gate bipolar transistor (IGBT), a rectifier, and a filter capacitor. Consequently, the power supply used in a conventional CO₂ laser system can be quite expensive. A bulky set-up is required for such power generation, and efficiency is generally under 10% [9, 10].

To overcome these problems, a series-parallel resonant converter (SPRC) is adopted in the current study. Depending on their intended use, the conventional resonant converters are composed of two types: LLC or LCC [11, 12]. In particular, LCC resonant converters are used to drive gas discharge lamps, such as high-intensity discharge (HID) lamps and fluorescent lamp. The switching frequency of these lamps must be controlled because resonant frequency is dependent on the equivalent impedance. If the switching frequency is not controlled, the lamps or switching elements in the lamps will be damaged by the unstable operation that results when the operating frequency fluctuates from the resonant frequency. However, in case of a CO₂ tube, the initial and final resonance points are same because the equivalent impedance before and after discharge of CO₂ from the tube is high and a current-limiting resistor is used; however, the resonance gain changes slightly. Thus, the proposed LCC resonant converter can be used to adjust the power generated using the CW CO₂ laser. In this paper, the design of the LCC resonant converter that can precisely adjust the output power of a CW CO₂ laser is described. The proposed LCC resonant converter is composed of a series-parallel

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resonant tank, an HVHF transformer, a half-bridge circuit designed to act as a metal-oxide semiconductor field-effect transistor (MOSFET), a three-stage Cockcroft-Walton voltage multiplier, and a DSP microprocessor for variable frequency control. The power generated by a CW CO₂ laser can be precisely adjusted by adjusting the voltage gain. The voltage gain depends on the total capacitance, which is equivalent to the input capacitance of the Cockcroft-Walton voltage multiplier, the parasitic capacitance of the HVHF transformer connected in parallel, and the series-parallel resonant tank that causes resonance. The voltage gain is changed by controlling the variable frequency using the DSP microprocessor. Techniques involving the use of the LCC resonant converter have several advantages. First, in the case of operation at high frequencies, considerably small-sized passive components, such as an HVHF transformer and filter, are required. Furthermore, the ripple is small. Second, system efficiency is high; switching losses are few because of the zero-voltage switching (ZVS). Third, the laser output energy can be precisely adjusted on resonance gain.

2. Description of CO₂ laser circuit

2.1 Description of CO₂ laser and system components

Fig. 1. Components of a supply system with a CO₂ laser

Fig. 1 shows the components of a power supply system in a CO₂ laser. The conventional 23 W CO₂ laser system (operating at a wavelength of 10.6 μm) is excited using LCC resonant converter. The optical resonator with an overall reflectivity of 90% has a 450 mm long Pyrex tube with an inner diameter of 19 mm. The discharge length is approximately 350 mm. The laser system is cooled by water.

2.2 Design of an LCC resonant converter and fundamental approximation

The schematics of an LCC resonant converter with a three-stage Cockcroft-Walton voltage multiplier are shown in Fig. 2. In reference to a previous paper [13], the Cockcroft-Walton circuit can be considered equivalent to a bridge rectifier and as equivalent input capacitance of

Cockcroft-Walton (C_E) as shown in Fig. 3. The equivalent resistance can be estimated from Fig. 3, from which the load on the resonant circuit for carrying out AC analysis can be determined.

Fig. 2. LCC resonant converter laser with three-stage Cockcroft-Walton voltage multiplier

Fig. 3. AC equivalent circuit for LCC resonant converter

Fig. 4. Equivalent circuit for LCC resonant converter

The transformer resistance can be ignored because it is very small. The equivalent circuit for an LCC resonant converter can have a primary-side leakage inductance (L_{lkp}), a resonant capacitance (C_r), a magnetizing inductance (L_m), a secondary-side leakage inductance (L_{lks}), a parasitic capacitance (C_p), and an equivalent input capacitance of the Cockcroft-Walton (C_E) and a voltage multiplier (α), as shown in Fig. 4.

Here, L_m can be ignored because the LCC resonant converter is operated at a high frequency and L_m is considerably higher than the leakage inductance. As shown in Fig. 5, L_{lkp} and L_{lks}/n^2 are connected in series, and C_p and C_E are connected in parallel (represented as L_r and C_p , respectively). Thus, the equivalent circuit for LCC resonant converter can be simplified (Fig. 5).

The root mean square (rms) value of input voltage V_{ac_rms} is given by Eq. (1), whereas the rms value of the input current I_{ac_rms} is given by Eq. (2).

$$V_{ac_rms} = \frac{\pi}{2\sqrt{2}} V_o \quad (1)$$

Fig. 5. Equivalent circuit of the LCC converter

$$I_{ac_rms} = \frac{2}{\pi} \sqrt{2} I_o \quad (2)$$

Using Eqs. (1) and (2), the equivalent AC resistance can be presented as Eq. (3), whereas R_{ac} can be represented by considering the transformer turns ratio ($N_p / N_s = 1 / n$) as Eq. (4).

$$R_{ac} = \frac{V_{ac_rms}}{I_{ac_rms}} = \frac{\pi^2}{8} \frac{V_o}{I_o} = \frac{\pi^2}{8} R_o \quad (3)$$

$$R_{ac} = \frac{\pi^2}{8n^2} R_o \quad (4)$$

Thus, the voltage gain of the simplified AC equivalent circuit can be calculated using Eq. (5).

$$\frac{E_{OUT}}{E_{IN}} = \frac{1}{\left(1 + \frac{n^2 C_p}{C_r} - \omega^2 n^2 L_r C_p\right) + j \frac{1}{R_{ac}} \left(\omega L_r - \frac{1}{\omega C_r}\right)} \quad (5)$$

The voltage relationships can be derived using Fig. 2, as shown in Eqs. (6) and (7).

$$E_{OUT} = \frac{\pi}{2\sqrt{2}} V_o \quad (6)$$

$$E_{IN} = \frac{2\sqrt{2}}{\pi} V_{IN} \quad (7)$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{8}{\pi^2} \frac{E_{OUT}}{E_{IN}} \quad (8)$$

Q factor is defined by Eq. (9).

$$Q = \frac{n^2 \omega_0 L_r}{R_o} \quad (9)$$

$$\text{where } \omega_0 = \frac{1}{\sqrt{L_r C_T}}$$

$$C_T = \frac{n^2 C_r C_p}{C_r + n^2 C_p}, \text{ and } L_r = L_{lkp} + L_{lks} / n^2$$

Finally, the voltage gain of the LCC series-parallel resonant converter can be calculated using Eq. (10).

$$\frac{V_o}{V_{IN}} = \frac{1}{\frac{\pi^2}{8} \left(1 + \frac{n^2 C_p}{C_r} - \omega^2 n^2 L_r C_p\right) + jQ \left[\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega \left(1 + \frac{C_r}{n^2 C_p}\right)}\right]} \quad (10)$$

2.3 Design of a three-stage Cockcroft-Walton voltage multiplier

The design of the Cockcroft-Walton voltage multiplier that acts as the base for the proposed LCC resonant converter is very important because the output voltage ripple is dependent on the voltage multiplier. Furthermore, according to the Eq. (12), the output voltage of Cockcroft-Walton multiplier is dependent on the frequency. Thus, the output power of the CW CO₂ laser can be precisely adjusted by varying frequency. The maximum voltage of the multiplier can be calculated using Eq. (12).

The voltage drops across C_1 , C_2 and C_3 of the Cockcroft-Walton circuit can be expressed as Eq. (11). Using Eqs. (11) and (12), the ripple can be calculated as shown in Eq. (13).

$$\Delta V_0 = \frac{I_0}{2 \cdot f} \left(\frac{3}{C_2} + \frac{2}{C_4} + \frac{1}{C_6} \right) \quad (11)$$

$$V_0 = 6 \cdot V_{RI_max} - \frac{I_0}{f} \left(\frac{9}{C_1} + \frac{15}{2 \cdot C_2} + \frac{4}{C_3} + \frac{3}{C_4} + \frac{1}{C_5} + \frac{1}{2 \cdot C_6} \right) \quad (12)$$

$$\text{ripple}(\%) = \frac{\Delta V_0}{V_0} = \frac{\frac{I_0}{2 \cdot f} \left(\frac{3}{C_2} + \frac{2}{C_4} + \frac{1}{C_6} \right)}{6 \cdot V_{RI_max} - \frac{I_0}{f} \left(\frac{9}{C_1} + \frac{15}{2 \cdot C_2} + \frac{4}{C_3} + \frac{3}{C_4} + \frac{1}{C_5} + \frac{1}{2 \cdot C_6} \right)} \times 100 \quad (13)$$

Thus, the voltage drop and ripple can be determined by Eqs. (12) and (13).

3. Experimental results and discussion

An experimental prototype of the converter was fabricated in the laboratory. Table 1 shows the parameter of

Table 1. Parameters of the transformer with a resonance tank

Parameters	Value
Transformer turn ratio($N_p : N_s$)	1 : 3
Resonant capacitance (C_r)	2.3 nF
Primary self-inductance (L_l)	901.31 μ H
Primary leakage inductance (L_{lkp})	270.41 μ H
Magnetizing inductance(L_m)	630.9 μ H
Secondary self-inductance (L_2)	8.1 mH
Secondary leakage inductance (L_{lks})	2.43 mH
Secondary the parasitic capacitance (C'_p)	663.38 pF
Equivalent input capacitance of Cockcroft-Walton (C_E)	34.5pF
Cockcroft-Walton capacitance	2 nF

transformer with a resonance tank. Several analyses and selection procedures are required to operate a CO₂ laser.

First, the plot of the equivalent input capacitance of Cockcroft-Walton circuit versus frequency must be prepared because the total capacitance, in which the equivalent input capacitance of a three-stage Cockcroft-Walton voltage multiplier (C_E) and the secondary the parasitic capacitance (C'_p) of the transformer are connected in parallel, is involved in resonant tank, and affects the resonant phenomenon. In the case of the total capacitance (C_p) of the transformer, additional capacitance may be added to obtain high resonance gain.

Second, resonance gain curve of the resonant tank must be prepared because it is related to the resonance characteristics and voltage gain. Thus, the resonance gain curve of resonant tank is normally obtained by power simulation tools, such as MATLAB and PISPICE.

However, in this paper, a new measuring technique using spectrum analysis is used to obtain the exact resonance characteristics and voltage gain of resonant tank. Third, the operating frequency is selected by considering ZVS switching, ripple, and drop of the output voltage.

Fig. 6. Plot of equivalent input capacitance of Cockcroft-Walton circuit versus frequency

As mentioned above, the equivalent input capacitance of Cockcroft-Walton circuit is measured using an LCR meter (LCR-8101G); Fig. 6 shows the equivalent input capacitance as a function of frequency. An average value of approximately 34.5pF is obtained in the operating range of 187.5 kHz to 370 kHz.

Total capacitance, in which the equivalent input

capacitance (C_E) and the parasitic capacitance (C'_p) of the transformer are connected in parallel, contribute to the initial high resonance gain. The CO₂ laser operates if the initial trigger voltage is high.

Fig. 7. Spectra of the designed transformer with a resonant tank for different loads

Fig. 7 shows the spectra of the designed transformer, including a resonant tank and an equivalent input capacitance of the Cockcroft-Walton circuit versus loads, obtained using a spectrum analyzer (WaveRunner 104Xi-A) and an AC sweep of the function generator (WF1974). The resonant frequency of the designed transformer has two resonance characteristics, similar to the characteristics of the LLC and LCC resonant converter.

As shown in the Fig. 7(a), LCC resonance phenomenon is observed at high frequencies because the impedance at both the ends of L_m are considerably higher than those at both the ends impedance of C_p . In addition, as shown in Figs. 7(b), (c), and (d); the LCC resonant frequency shifts to the left side as the load increases. As mentioned above, in the case of the LLC resonance, the phenomenon is observed at low frequencies and resonant frequency because the impedance at both the ends of C_p are considerably higher than those at both the ends of L_m . Thus, as shown in Fig. 7(b), LLC resonant frequency shifts to the right side as the load decrease. Similarly, the LLC resonant frequency shifts to the right side. In the case of no load and 600kΩ, the resonant frequency does not change.

Moreover, when the 23W CO₂ laser is discharged, the value of its internal resistor has more than 600kΩ. Thus, the resonance curve in the Fig. 7(a) is used to select resonance frequency. The region on the right side of the LCC resonant frequency is selected as the operating range because the ripple and output voltage drop decrease with an increase in frequency and because ZVS of the MOSFET can be realized by switching when the operating range is on the right side of the LCC resonant frequency.

Fig. 8 shows the output voltage and current waveforms for a steady state operation under the DC discharge voltage of 9.25kV. The output power of the CW CO₂ laser (23 W) is measured by a power meter (Plus+ 600534) for CW CO₂ laser. In addition, the CW CO₂ laser is excited using DC glow discharge. An output voltage ripple of approximately 1.62% is observed when the switching frequency is high.

Fig. 9 shows the plot of the laser output power obtained

Fig. 8. Output voltage and current waveforms for steady state operation

Fig. 9. Laser output power versus operating frequency

when using the designed LCC resonant converter versus operating frequency. The operating frequency ranges between 187.5 kHz and 370 kHz, and output power from 4.3 W to 23 W is obtained in this range of operating frequency.

The function of the laser power and frequency can be obtained by MATLAB curve-fitting tool, as shown in Eq. (14) and Fig. 10:

$$P(x) = 0.0003x^2 - 0.2669x + 62 \quad (14)$$

Fig. 10. Experimental data and MATLAB fitting curve for laser output power

Fig. 11. Laser output power versus frequency after applying the MATLAB fitting function

Fig. 12. Waveforms of voltage and current waveforms with ZVS operation

After the MATLAB fitting function is applied to the DSP controller, the laser output power and efficiency are measured (Fig. 11). Laser output power increases as frequency decreases because the input power is inversely proportional to the switching frequency. However, system output efficiency remains practically the same and is not dependent on the operating frequency. Thus, the switching loss is very low in the case of ZVS. The maximum efficiency of the laser system is approximately 16.5%. The waveforms in the ZVS operation, including voltage and current waveforms are shown in Fig. 12.

4. Conclusion

In this paper, an LCC resonant converter with a Cockcroft-Walton voltage multiplier is proposed. When this LCC resonant converter is used, the switching loss in the case of ZVS is very low. Furthermore, the Cockcroft-Walton voltage multiplier facilitates decrease in the diode ratings, isolation requirement, and transformer turns ratio, as well as an increase in the total output filter capacitance. The proposed LCC resonant converter is driven at an

operating frequency from 187.5 kHz and 370 kHz by a DSP microprocessor; therefore, it is able to precisely adjust the laser output power between 4.3 W and 23 W. The maximum efficiency of the power supply system is 16.5%, and the minimum ripple of output voltage is approximately 1.62%. The MATLAB curve fitting tool is used to perform curve fitting of the output power of CO₂, thereby facilitating optimal control of the output power. Furthermore, the proposed LCC resonant converter will be very effective if applied to DSSC sealing and glass cutting that require precise control of laser power.

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