 The Open Electrical and Electronic Engineering Journal, **2008**, *2*, 36-40

Two-Stage Radio Frequency Power Generator-Amplifier Design for a TEM00 CO_2 Slab Waveguide Laser

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Abstract: This letter presents the results of the research conducted on the design, construction and test of a two stage radio frequency power generator-amplifier directed adapted to an in-house-built compact CO_2 waveguide laser. The main characteristic of this power supply lies in the fact its design is based on MOSFET technology for both the oscillator and the amplifier stages. RF output power is centered at 81MHz frequency signal between 100W to 150W. The two-stage system device has a minimum electric conversion efficiency of 64%. Consequently, the laser head and RF excitation design must have an electrical termination of 50Ω impedance and the whole system may include a proper matching circuit. The overall test, for the entire system: RF excitation along with our CO_2 laser head, is made with a typical gas mixture of CO_2-N_2-He with proportion of 1:1:3 correspondingly and at a final pressure of 40Torr. Under these specific conditions, a maximum optical output power of 10.7W was obtained for an input feed RF power of 147W. Regarding the optical quality we measured the transverse mode of propagation TEM00 which indicate the entire system work very near the diffraction limit specifications for similar laser systems.

INTRODUCTION

CO_2 lasers are among the most prevalent industrial systems for manufacturing such as cutting, welding engraving, etc. These industrial processes require optical powers from a few to several thousands of Watts to fulfill any of these applications [1]. The Laser system design varies upon several key factors, such as the way the laser head (amplifying media) is excited. This can be accomplished by the use of direct current (DC), radio frequency (RF) or even microwaves [2]. In recent years, the most widely used are those with RF excitation. This RF power supplies are able to produce ionization of the molecular gas in the transverse-planar metallic electrodes, which form a capacitive waveguide structure coupled to an optical resonator [3]. The main reason why this technique is chosen today is because the RF signal changes its electrical sign from positive to negative or vice versa making the electrons oscillate without ever reaching ever the laser electrodes. This characteristic behavior leads to effectively a clean amplifying medium and prolongs the operational laser life. In our work, the optimum operational parameters to work with are in close to those given of Hall, *et al.* [4]. Our main purpose is to determine the optimum design for the excitation of our RF laser. RF power supplies are usually designed to generate the signal based on crystal oscillators or semiconductor devices as configured by Colpitts or Hartley oscillators. The semiconductor oscillator configurations enable the possibility of feeding several amplification stages by using the open loop technique [5, 6], which consists in having at most three general block gates. The resonator, amplifier and matching circuit will enable us to verify whether the excitation delivers a good quality signal output, which in turn leads us to have a stable oscillation signal at the closed-loop configuration of the required RF output power. These types of RF power generators have been shown to be the most reliable sources of generating stable laser plasmas in laser amplifying media [7, 8]. However, it is difficult to use this particular design when more RF power is required due to the difficulty of having more than one RF signal in phase. Therefore, and based in a one-stage amplifier, we propose the use of an oscillator to feed the amplifier circuit, based in a power MOSFET, in order to be able to change the excitation RF output power and consequently, the optical output power of the waveguide CO_2 laser.

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TWO-STAGE RF CIRCUIT DESIGN

Our electronic design is divided mainly into two parts, the oscillator stage and the amplifier stage. The oscillator is based on a MOSFET MRF136 with an operational power of 15W. The open loop design is given in Fig. (**1**). It can be seen that this stage is divided into three main parts as follows: The T-type resonator formed by L1, L2 and C1, with its amplification section and an L-type matching circuit of C3 and L4. The initial model values were the impedance input and output for the transistor and the design frequency of 81MHz. In order to use the transistor S-parameters and to determine the impedances, we use the drain-source voltage as VDS = 28V and current ID = 500mA. To achieve this, one has to use a voltage divider at the transistor gate, built with R1 and R2. Under these conditions, we obtained Zim= 7.55 – j7.85 as the input impedance and Zout = 9.7 - j8.45 as the output impedance. Input and output blocks for the corresponding resonator and adapter were designed to have a phase difference equal zero (for the oscillation condition to exist) and with an impedance of 100Ω. These values would have enabled us to have closed the loop and as a result to have 50W in parallel. Consequently, we have the maximum

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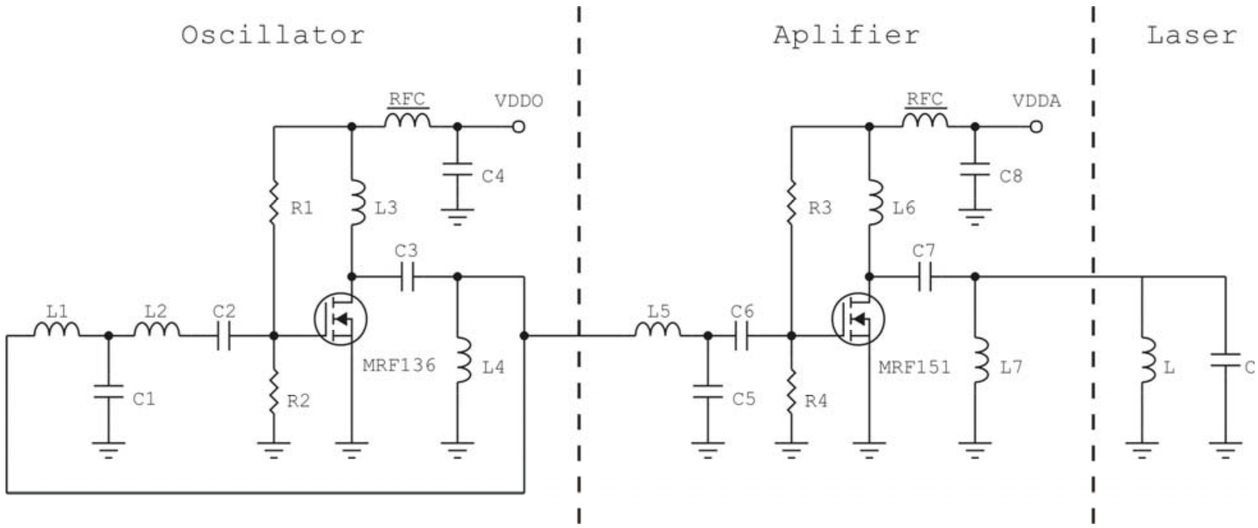

Fig. (1). Two stage RF excitation circuit diagram.

power transfer to our load. In this design we incorporate a de-coupled capacitor (C2) at the transistor gate and a RF filter for the VDDO pictured as a RFC shock coil and capacitor C4.

The amplifier circuit is based on a MOSFET MRF151, which is able to sustain, at most, 150W. Following the same procedure with the oscillator and to be able to use the transistor S-parameters, it is required here to have VDS = 50V and ID = 250mA for the Drain-Source voltage and Drain current. These values are achieved by using a voltage divider shown by R3 and R4 in Fig. (**1**). Under these conditions and with 81MHz as our design frequency, the input and output impedance of Zin = 2.1 – j1.3 and Zout = 5.5 – j3.85 were obtained. We add L-type impedance coupling nets at the input and output. As shown in Fig. (**1**), L5, C5 and L7, C7 represents the impedance nets and in addition we show the de-coupling capacitor C6 and a RFC filter at the VDDA section. The calculations for all components were evaluated using a Smith chart in the MATLAB® RF toolbox.

In order to smooth the progress of the circuit performance, special materials and components were minimized. Mica compression trimmer capacitors were used, such as 462, 463, 465 and the 469 from ARCO. These capacitors are robust and are able to sustain high powers. The values of these variable capacitors are in the range of 10pF to 790pF so that it is possible for us to fine tune the predicted design value. The inductors were built using copper wire 1mm in diameter. The overall circuit size was 10 cm x 20 cm using FR4 copper plate. In order to reduce parasitic capacitances formed between energized lines and ground plane of circuit, all the physical limits of the FR4 faces were interconnected with copper ribbons. Preformed perforations were made to improve the maximum interconnectivity of the transistor with its physical ground. A fan with approximately 30 CFM is required together with a fin heat sink to dissipate heat and sustain 150W on the transistor output [9].

EXPERIMENTAL LASER HEAD ASSEMBLY AND PARAMETER DESIGN

In a general way, the equivalent electrical circuit for the laser head is a passive element in which there can be optical losses. The hollow waveguide optical structure for the laser amplifying media has to be stabilized in terms of the gas ionization. In order to have a uniform intensity distribution in the discharge volume, it is necessary to have a uniform RF power distribution along the entire electrode length. To achieve this, it was necessary to treat the whole waveguide as an inductive-capacitive circuit by inserting parallel distributed inductors. The waveguide slab length is set to 377.35mm with a rectangular cross section of 20mm x 2mm. The separation of the electrodes and the discharge width was set using ceramic spacers (dielectric constant = 9) put side by side at a distance of 20mm. This configuration forms an equivalent circuit of three capacitors in parallel, C1, C2 and C3. Capacitance C1 and C3 are identical, formed by the metallic electrodes with ceramic spacers and C2 is the capacitor formed by the metallic electrodes and the gas mixture is in the hollow waveguide. The final waveguide incorporates an inductance, L, given by $L=1/(4\pi^2 f^2 C)$, (where C is the total parallel capacitance) which is parallel to satisfy the resonance frequency of 81 MHz for the LC circuit with the aim of transferring the net input power, from the RF generator, to the laser head. By using a BIRD400 Antenna Tester, a coupling efficiency was achieved better than 96% at the resonant frequency of 81 MHz. The optical resonator, coupled to the slab waveguide structure, operated at the appropriate temperature and the optimum optical output coupling is close to 9%. In our case, the optical resonator radius of curvature is R1 = 42.99cm and R2 = 38.79cm, with a resonator lateral magnification of 1.108. The optical coupling losses depend on the mirror separation from the hollow waveguide. The calculated coupling losses for a 6 mm separation in our setup result in less than 1%.

CIRCUIT PARAMETER ANALYSIS AND ITS PERFORMANCE

Our measurements were performed varying the oscillator output power from 0W to 8W by changing the circuit input power (DC). As seen in Fig. (**2**), a minimum of 3W of output power is necessary as this is the first perceptible signal is obtained, whereas the upper limit (8W) is where the maximum power the transistor can sustain in the amplification stage. It is important to point out that in this range a linear behavior is clearly perceived. The conversion efficiency for our oscillator circuit was between 63% and 64%.

Output power variations of the amplifier stage are dependent on the power delivered by the oscillator, which in turn depends on the DC input power of the whole system. Fig. (**3**) shows the overall output power delivered by from the amplifier to a dummy load in terms of the oscillator stage RF signal of the circuit. These values are taken for VDS = 40V and VDS = 36V on the drain-source. The conversion efficiency of our amplifier circuit was between 65% and 85%.

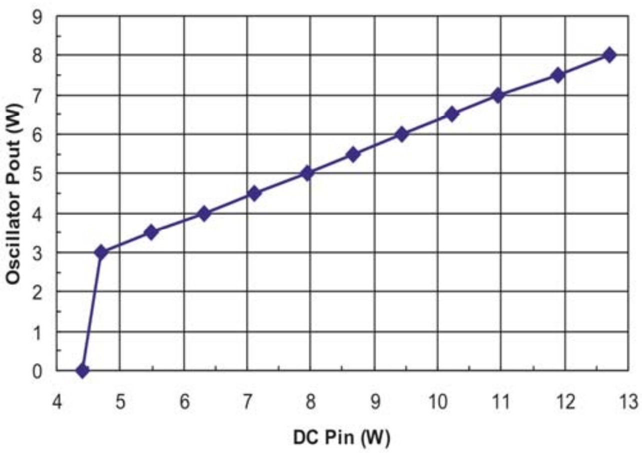

Fig. (2). Behavior for the oscillator output power in terms of the DC input power.

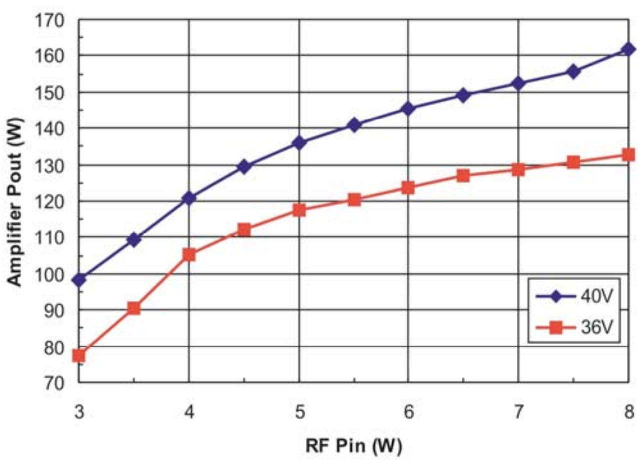

Fig. (3). Amplifier output power in terms of the oscillator RF signal taken as input for the amplifier stage.

The entire performance of our circuit design is shown in Fig. (**4**) and Fig. (**5**). Here one can see that the minimum conversion efficiency was to 64% for VDS = 40 V and an input power of 98W. These measurements were collected by using the power meter BIRD 43 and Power Analyst BIRD 4391A with a dummy load model 632.6 of 1kW @ 50Ω from M.C. Jones Electronics.

INEGRATION OF THE RF CIRCUIT INTO THE WAVEGUIDE LASER

As stated by Villagomez *et al.* [8], the laser amplifying medium (LAM) is built with an equivalent electrical ca-

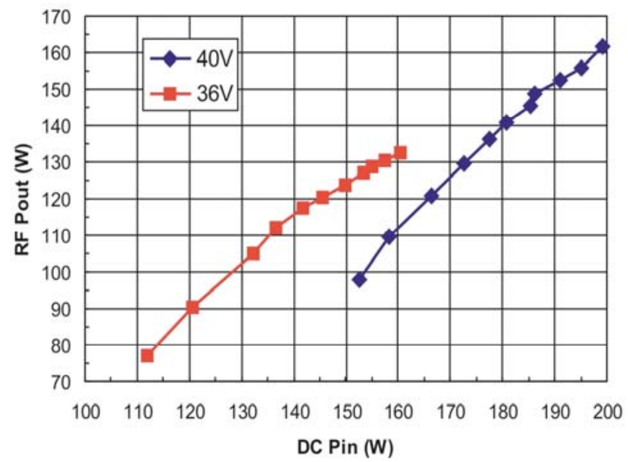

Fig. (4). Output power versus DC Input Power of the power supply.

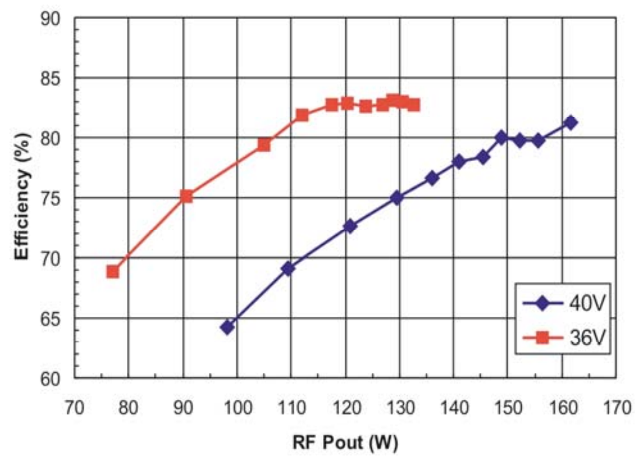

Fig. (5). Power supply efficiency for two input operating voltages for the entire circuit.

pacitive (C) circuit. In order to adapt the excitation to the LAM a set of inductors (L) were incorporated in parallel to achieve 81 MHz as the tune frequency of the equivalent laser amplifying media LC-circuit. A BIRD antenna tester AT400 was used to fine tune the whole LAM LC-circuit. This procedure gives us the possibility of eliminating the need of a traditional matching circuit normally employed in this kind of electrical circuit to guarantee the maximum energy transfer from the excitation to the LAM considered as the load. Once the LAM is electrically interconnected with the RF excitation, one step forward is to ignite (ionize) the laser head by filling the waveguide hollow with a gas mixture of CO_2-N_2-He with a proportion of 1:1:3 correspondingly. The laser head prototype is constructed such that it is possible to vary parameters such as the gas final pressure, mirror resonator alignment, waveguide and free space dimensions, mirrors coupling separation of the waveguide ends. The test pressure range was from 25Torr to 45Torr was selected for analysis and the optical output power recorded is as shown in Fig. (**6**). For the entire excitation laser test we achieved less than 10% of the RF reflected power back to the circuit source, in which case, the circuit prototype delivered 147W RF power into the laser amplifying media forcing it to deliver an optical output power for the extreme case of functioning. The extreme value for RF power of 147W was chosen because it is the maximum power extracted from our RF oscillator-amplifier circuit. As it can be seen in Fig. (**6**), the best value for the final cavity gas pressure was 40Torr. With this pressure, the maximum optical power extracted from the laser prototype was 10.7W, which represented an overall efficiency of 7.3% see Fig. (**7**).

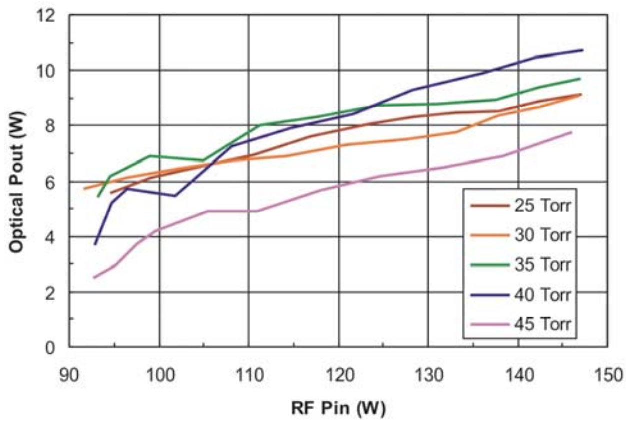

Fig. (6). Laser output power extraction versus the RF input power from the two stage circuit and using different final pressure in the laser amplifying media.

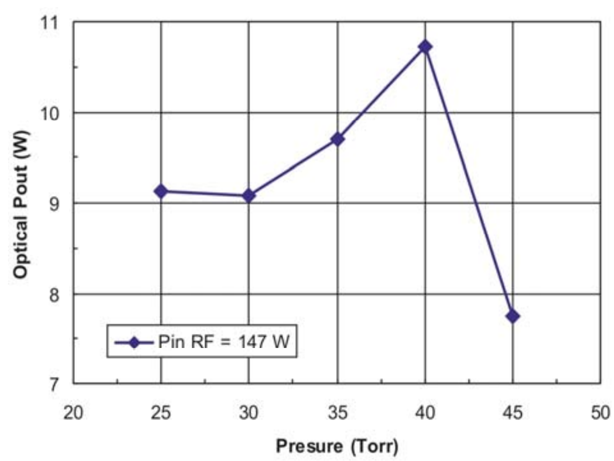

Fig. (7). Optical power variations for different gas pressures in the laser amplifying medium.

FINAL DIAGNOSTIC AND COMMENTS

As a final diagnosis, the experimental laser prototype was tested using both, RF excitation built in house and a commercial RF power amplifier such as the HENRRY 3000D from Radiodan. The laser prototype was successfully ionized with both power excitations operating at a final pressure of 40Torr. The maximum difference observed was of the order of ~ 2.3W, as one can see in Fig. (**8**).

As the final operational test, the optical power and beam size were measured with a beam profiler. The laser optical profile was captured in real time over about five hours to monitor the optical power and beam spot size. The stability of both parameters varied with power less than 0.5% which is good. Fig. (**9**) illustrates the result of the beam profile collected from the laser prototype. The deviation from this experimental profile for Gaussian beam is less than the 4%. The experimental beam size was 2.6mm for the TEM00 which is compared to the beam collected using a laser power analyzer model GS Field master from Coherent, Inc.

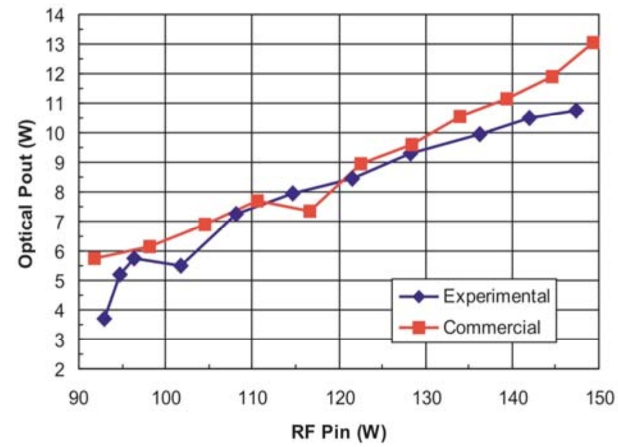

Fig. (8). Laser performance using both, a commercial and our experimental RF power supply.

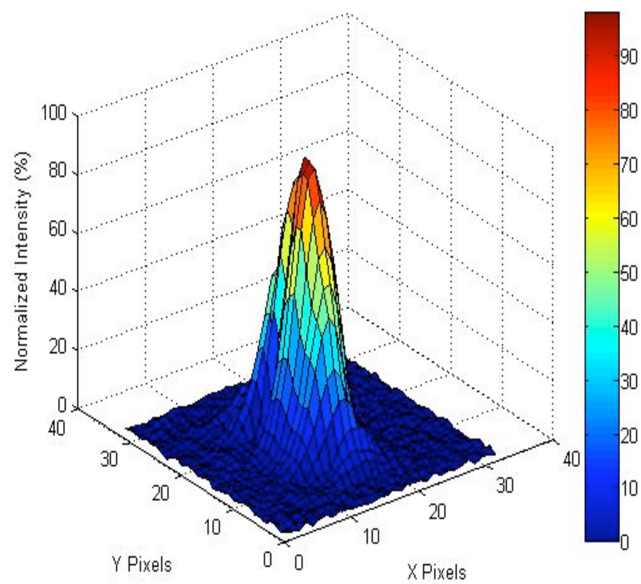

Fig. (9). Experimental laser beam profile recorded as mode TEM_{00}.

CONCLUSIONS

In this article we discuss the design and construction of a two-stage RF power generator-amplifier tuned to deliver a RF signal centered at 81MHz. This two-stage excitation was successfully adapted to the CO_2 waveguide laser amplifying media. An electrical DC-RF2 (DC input: RF-oscillator: RF-amplifier) with a power conversion efficiency of 64%. The laser prototype amplifying media was designed and calibrated to be tuned to 81MHz without the need of an impedance matching circuit between excitation and the load i.e. the laser amplifying media. The results presented here were obtained for some specific laser parameters, such as the final gas pressure of 40Torr, and the excitation delivering 147W of RF power. One important feature for our oscillator is the possibility of feeding two MOSFET amplifier circuits simultaneously. As a final remark we measure the optical quality of the laser beam finding that the optical profile was very near the diffraction limit for similar laser systems.

ACKNOWLEDGEMENTS

The author acknowledges the support received from the Mexican Research Council grant No. 42944 and to Mr. Raul Monsalve for his assistance in the assembly of circuits.

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Received: December 31, 2007 Revised: April 10, 2008 Accepted: April 15, 2008