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Usage of Energy Storage Capacitors in TE Gas Laser Pulsers

Pallavi Raote[1*], J. P. Nilaya[2] and D. J. Biswas[3]

[1]Department of Physics, K. J. Somaiya College of Science and Commerce, Mumbai – 400077, Maharashtra, India; pallavi.raote@somaiya.edu

[2]L and PTD, Bhabha Atomic Research Center, Mumbai – 400085, Maharashtra, India

[3]C1701, Tharwani Heritage, Sector-7, Kharghar, Navi Mumbai, India

Abstract

An energy storage capacitor is crucial for both electrically pumped and optically pumped pulsed lasers. In electrically pumped lasers, the energy stored in the capacitors is directly deposited into the lasing medium, while in optically pumped lasers, it energizes the flash lamp that, in turn, pumps the lasing medium. We discuss here the application of energy storage capacitors in the operation of electrically pumped pulsed gas lasers. Increasing the operating pressure of the gain medium, a prerequisite for obtaining higher energy from the laser, has resulted in great advancements in the gas laser pulse technology. This progress has led to the development of transverse electric discharge pumping, enabling easy scalability of gas pressure and achievable output power. An ideal TE pulser efficiently charges the capacitor to an appropriate voltage with minimal energy dissipation on the charging element and facilitates a rapid and uniform transfer of this stored energy into the lasing medium before a glow-to-arc transition can set in. Various types of pulser circuits employed to energize pulsed gas lasers are described in this paper.

Keywords: Energy Storage Capacitor, Gas Laser Pulser, Spark Gap

1. Introduction

An electrical pulse is an indispensable part of a laser system which transfers energy stored in the capacitors directly (e.g., in a CO_2 laser) or indirectly (e.g., in an Nd-YAG laser) into an active medium to create population inversion, a prerequisite for the operation of a laser. This assumes higher significance in the operation of a gas laser where high voltage discharge has to be tailored for efficient excitation of the lasing medium as well as sustenance of the glow discharge. Electrons of appropriate energy in the glow discharge collide inelastically with the active species, causing their vibrational excitation that results in effecting population inversion and, in turn, lasing under suitable conditions.

Gas lasers, where the lasing medium is a gas or a mixture of gases, intrinsically offer efficient and high-power emission with narrow emission line width over a wide range of electromagnetic spectrum. The output wavelength of laser emission is decided by the gas that participates in the lasing action. Eg, the CO_2 laser, the most powerful laser in the MIR region, operates in the 9-11µm region1 while the He-Ne laser operates in the visible region and eximer lasers operate in UV/VUV region[2]. Recently P. Chavaliar demonstrated the wide tunibility of various gas lasers in Tera Heartz region[3]. The possibility of scaling up the output power by increasing the length of a longitudinal discharge in the case of a Continuous Wave (CW) is limited by the requirement of high DC voltages in addition to alignment issues. Increasing the operating pressure of the active medium and operating the laser in the pulsed mode is an attractive option. Voltage is applied in a direction transverse to the optic axis across the volume of the active medium, and hence these lasers are called Transversely Excited (TE) gas lasers. With increasing operating pressure, the glow-to-arc transition time too reduces and therefore the duration of the discharge has to be appropriately tailored. An efficient laser pulser takes energy

**Author for correspondence*

from the source and converts a major portion of this energy as the internal energy of the lasing medium that is eventually realized as population inversion. We discuss here, various aspects of a TE laser pulser including the charging of the capacitor, the role of the switch, tailoring of the discharge for efficient excitation of the lasing medium, reducing the discharge duration and switchless operation of a TE laser.

2. TE Gas Laser Pulser: Working Principle

Schematic of a typical TE gas laser pulse is shown in Figure 1. When the high voltage capacitor 'C' is charged to an appropriate voltage (~ few tens of KV) through a charging element, the switch closes, allowing it to deposit the stored energy into the load, here the active medium of the laser. The value of the charging current makes a way towards the ground through the charging bypass, which is judiciously chosen so that while it enables charging of the capacitor, it doesn't alter the charging time constant much (R_{CE}>> R_{CB})nor does it provide an easy path for the discharge of the capacitor (R_{CB}>> RLaser).

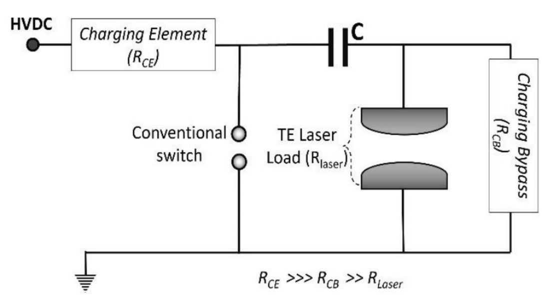

Figure 1. Schematic of typical laser pulser circuit.

To ensure the efficient energy transfer from the capacitor to the laser load, the discharge must be over before arcing sets in. This requires a reduction in the discharge loop inductance of the pulser circuit which is mainly governed by the inductance of the switch and capacitor. This emphasizes the need for a high voltage low self-inductance energy storage capacitor as well as a fast-closing switch for the gas laser pulsers circuit design.

2.1 High Voltage Switches Used in TE Gas Laser Pulsers

As stated before, the transfer of stored energy from the capacitor to the laser load is achieved via a switch. With increasing operating pressure, the glow-to-arc transition time reduces, implying that the discharge should extinguish before the formation of filamentary arcs. This necessitates the usage of a switch with the inherent capability to sustain high di/dt. Furthermore, depending on the type of laser, it should be operable at high voltages (e.g., typically ~25-30kV for a 1J TEA CO_2 laser) and current levels (several kiloamperes as the transverse glow discharge resistance is low, typically several ohms only) while facilitating a discharge. The recovery time of the switch also determines the repetition rate of the laser pulser circuit.

The most basic switch, a spark gap can satisfy the described conditions and is most commonly used in single-shot pulse gas laser circuits. However, the arc mode operation of a spark gap renders it unsuitable for prolonged repetitive operation. In such cases, thyratron, which works in Townsend discharge, replaces the spark gap making it more compatible for repetitive operation[4]. But Thyratrons suffer from limited life and are expensive.

All Solid State Exciters (ASSE) along with magnetic compressors are also used as switches in TE gas laser systems for repetitive operation[5]. However, these types of switches have low wall plug efficiency due to the energy loss at each stage of magnetic pulse compression in addition to making the system bulky, particularly at larger input energy.

2.2 Charging and Discharge Pulse Modulation Constraints

Thus, the working of any gas laser pulser circuit consists of 1) charging and 2) discharge of the energy storage capacitor. For better efficiency, it is essential that minimum energy should be dissipated on the charging element during the charging process and once charged, the energy storage capacitor must be able to discharge its energy homogeneously in the laser load through a glow discharge mode within an optimum time[6]. The homogeneity of glow discharge plays a vital role in deciding the temporal and spatial characteristics of the output beam. In elastic collisions of electrons form discharge current with gas molecules leading to the population inversion.

Hence, it is understandable that the di/dt should be high enough and the value of voltages (that in turn decide the energy distribution of the electrons) appropriate to facilitate a swift establishment of population inversion and the attainment of the threshold state for lasing before spontaneous emission has chance to dissipate the inversion. This should occur before the population has a chance to dissipate from the upper laser level due to spontaneous emission. Typically, at atmospheric pressure operation of a CO_2 laser, the discharge duration is < 1 μs (~ glow to arc transition time), and the onset of laser pulse w.r.t. the discharge has a delay of ~ several hundred ns. Figure 2 illustrates this aspect of the laser operation.

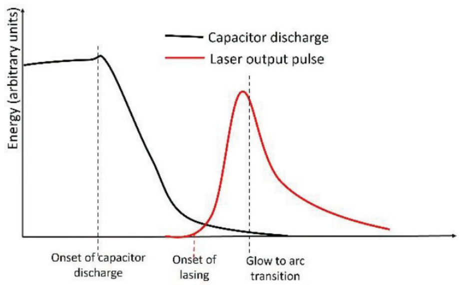

Figure 2. Diagrammatic representation energy input in laser load through glow discharge and laser output pulse onset in the time domain.

3. TE Gas Laser Pulsers

A wide variety of pulser circuits is made use of in the operation of TE gas lasers[7]. We discuss below some of the commonly used pulser circuits along with a self-switched pulser which was developed in our lab where an external switch is not employed in the pulser circuit.

3.1 Simple RC Charging Circuit

Figure 3 shows the simplest charging circuit where the condenser is charged through resistance and is normally employed for single shot or low repetition rate operation of a laser[8].

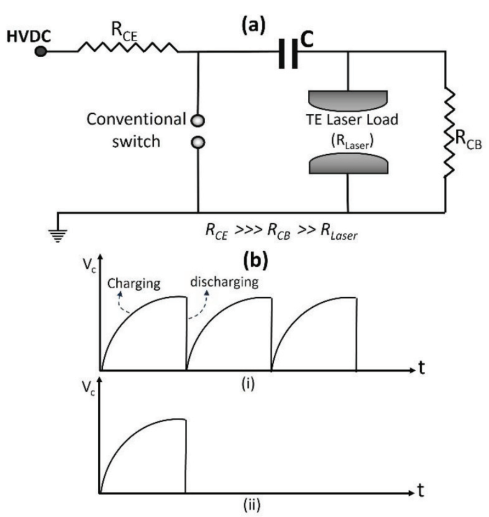

Figure 3. **(a)** schematic of R-C charging based pulser circuit **(b)**Voltage across the laser load in a typical TE laser pulser **(i)** when spark gap recovers **(ii)** when spark gap not recovered.

The switch employed for this purpose is usually a spark gap. However, resistive charging is unsuitable for high repetition rate operation as it is only 50% efficient and inhibits the recovery of the switch following a discharge unless special care is taken.

3.2 Commond Resonant Pulser

For repetitive operations as well as to achieve better efficiency, inductance is used as a charging element with an additional switch as shown in Figure 4. In this circuit, charging as well as discharge is controlled by an external trigger, i.e., on command hence this circuit is also called a command resonance-based pulser. When trigger T1 arrives, S1 closes and charging of the capacitor is initiated through inductance. Once the capacitor gets fully charged to ~2Vs, the charging current becomes zero and S1 goes to the off state automatically, leading to the isolation of the power supply from the remaining circuit.

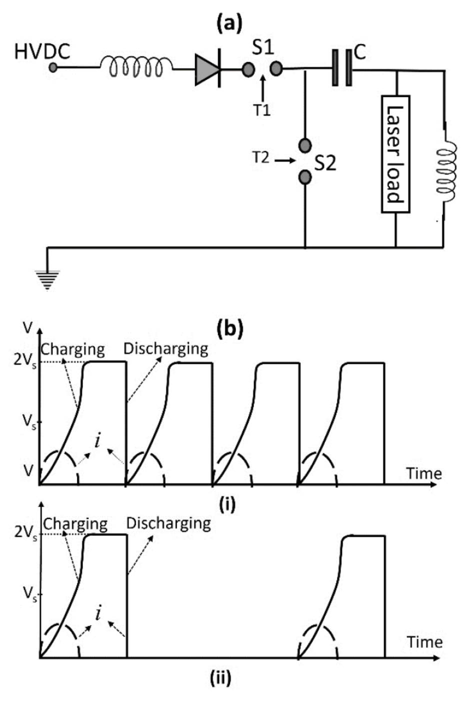

Figure 4. **(a)** Schematic of command resonant charging pulser **(b)** Voltage and current charging and discharging **(i)** with max. repetition rate operation **(ii)** with a 20% duty cycle.

Now S2 is made to close with T2 causing the capacitor to discharge into the laser load. Throughout this discharge phase, the open S1 doesn't permit the flow of any short-circuit current through the conducting switch. Moreover, it may be noted unlike R-C charging, the charging current here slowly builds up from zero.

However, the main disadvantage of this circuit is the design complexities. As both the anode and cathode of the charging switch (S1) have to be maintained at high voltage, an isolation transformer is essential for filaments. Two switches are essential and false triggering of S1 during the discharge cycle, which cannot be ruled out due to the presence of high EM noise, can result in the flow of very high short circuit current[7].

3.3 Double Discharge Pulser Circuit

The pulser circuits discussed in previous sections focus on efficient charging and discharging.

However, preconditioning of discharge volume with sufficient electron density is essential for stable discharge and high energy loading. This can be accomplished by a pre-discharge that creates UV photons capable of preconditioning the discharge volume before striking the main discharge[9]. Here, an auxiliary arc discharge between several spark channels placed judiciously in the vicinity of the main electrodes precedes the main discharge. The UV photons released from this auxiliary discharge interact with the active medium and ionize the gas mixture, increasing the electron density to ~10^7/cc as against 10^4/cc under normal conditions. After this auxiliary discharge, energy stored from the capacitor is dumped into the laser load.

A typical Marx bank-driven spark gap switched double discharge pulser circuit is shown in Figure 5. The capacitors C_1 and C_2 are resistively charged to the supply voltage (V_s) in parallel and are made to discharge in series into the load. The closure of Sw_1 results in a transient series connection of C_1 and C_2 causing the voltage across them to add up. This over-volts Sw_2 leading to its closure and producing the high voltage impulse across the load. As soon as Sw_2 closes, due to the very small gap between pre-ionising spark channels, they close first. The UV photons generated in the sparks along the length of the discharge cause pre-ionisation and reduce the impedance of the main discharge gap. The pre-ionising current is limited by the capacitance value of Cpre and the main discharge takes place after a delay decided by C_{pre} and the inductance of the circuit. Doubling of voltage helps reduce the requirement on power supply while capacitive ballasting of pre-ionising pins helps limit the pre-ionisation current.

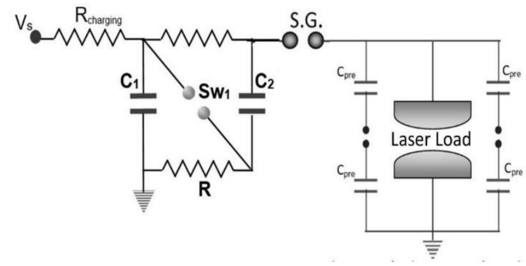

Figure 5. Marx Bank driven double discharge TE laser pulser with capacitance ballasted pre-ionising sparks.

3.4 Spiker Sustainer Pulser Circuit

In the pulser circuits discussed now, a main energy storage capacitor charged to a high voltage provides the energy to initiate glow discharge, sustain it and also cause excitation. While the initiation of glow discharge demands a higher E/N, its sustenance and excitation of the laser medium require much lower E/N. Hence independently managing the initiation and continuation of discharge is sought after, and is managed by the spiker sustainer circuit as shown in Figure 6(a).

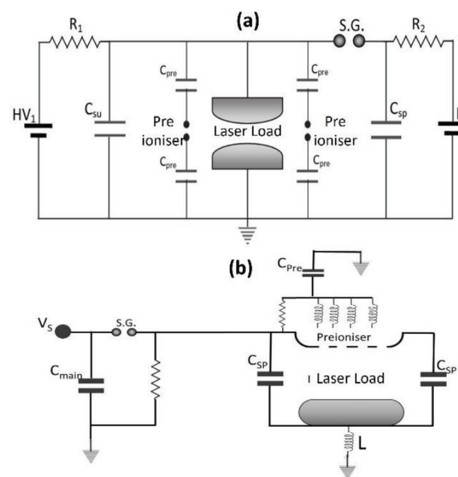

Figure 6. Schematic of Spicker-sustainer pulser circuit **(a)** with dual power supply **(b)** with single power supply.

A spiker capacitor (C_{sp}) is charged to an elevated voltage while the sustainer capacitor (C_{su}) is charged to a much lower voltage ($C_{sp} << C_{su}$). Following the closure of the spark gap connected to the spiker capacitor, a very high voltage impulse is impressed across the electrodes resulting in the initiation of high voltage low energy spiker discharge. The sustainer capacitor then directly discharges into the load and sustains the discharge. The energy used in the spiker discharge is significantly lower (usually around 10% of the total energy), thus the load on the switch is notably reduced. This results in an extended lifespan for the switch[7]. The same result can also be achieved by employing a single high-voltage supply and a single energy storage capacitor as shown in Figure 6(b). When C_s is appropriately charged, the switch closes and initiation of pre-ionisation through auxiliary spark pre-ioniser occurs. At the same time, C_{sp}, being much less than C_{sus}, gets charged to an elevated voltage and generates spiker pulses that initiate discharge. The voltage across C_{sus}, after having powered the spiker and pre-discharges, drops enough to be able to efficiently sustain the discharge and cause excitation of the lasing medium[11].

3.5 Self-Switched Mutually Coupled Pulser

As we have seen, the preioniser sparks produced across tiny pins placed along the length of the discharge are essential for the operation of a laser. We have operated a pulser where these have been used to self-switch the laser without any external switch[12-14]. LC inversion technique coupled with spiker sustainer configuration with mutually coupled spark pre-ionisers forms the heart of this system. A high-voltage DC power supply charges condensers C_1 and C_2 to an appropriate potential V_b, the self-breakdown voltage of the switch cum preioniser array.

With the closure of all the parallel pre-ioniser gaps, the voltage at 'A' oscillates from $+V_b$ to $-V_b$ causing a high voltage (V_{LC}) impulse which appears across the laser load. Owing to dissipation within the pre-ioniser loop, the voltage across the laser electrodes is slightly less than twice the supply voltage (V_b), which leads to a closer inter-electrode gap. Using a capacitor (C_{sp}) with a significantly smaller value than C_1 and C_2 across the laser electrodes ensures a dependable, arc-free operation of the laser discharge. This is likely due to the high di/dt (rate of change of current) associated with C_{sp} discharging into the laser load. C_1 and C_2 also discharge into the lasing medium, albeit at a slower rate, thereby sustaining the discharge. Interestingly, introducing a lumped inductance (l) in the discharge path of C_1 and C_2 not only enhanced the laser's electro-optic efficiency but also allowed control over the peak power and duration of the laser pulse emission n.

Further, in this arrangement, only a small fraction of the stored energy flows through the pre-ioniser pins. Owing to the parallel configuration of switch cum pre-ioniser utilized in the operation of switchless TEA CO_2 laser, the discharge currents get shared among the multiple parallel spark channels ensuring their faster and easier recovery that, in turn, results in better operational life and repetition rate capability. This excitation technique enables the usage of a single source to power the pre, spiker and sustainer discharges without the use of any extraneous switch[13,14].

The use of an LC inversion-based excitation scheme enhances the voltage across the laser load due to voltage doubling and therefore, reduces the requirement on the power supply. In addition, it also reduces the loading of the preioniser spark channels as only a small fraction of the energy stored is dissipated into the pre-ionisation spark channels. This has been found to increase the electro-optic efficiency of the self-switched laser.

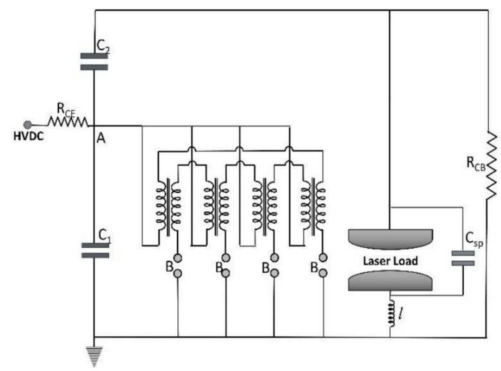

Figure 7. Switchless pulser of TEA CO_2 laser with mutually coupled parallel spark preioniser.

4. Conclusion

In this paper various types of TE gas laser pulsers that are employed to transfer the energy stored in a capacitor into the laser load are discussed. Obtaining a homogenous glow discharge and efficient transfer of energy into the lasing medium are of prime importance and ways to optimize the pulsers to achieve this goal have been reviewed.

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