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Development of Low-Cost Prototype N_2 Laser System and Laser-Induced Fluorescence of Pyranine

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Abstract: This work aims to a detailed description of the development of a prototype Transversely Excited Atmospheric (TEA) nitrogen laser and its high-tension electrical pump source, along with its application study of Laser-Induced Fluorescence (LIF). The high-tension pump source is designed and simulated by using NI Multisim to study the voltage behavior at different points. The high-tension pump source is constructed using the flyback transformer. The open-air laser cavity is designed and simulated by using Zemax Optic Studio. Blumlein transmission line equivalent of nitrogen laser is designed in NI Multisim, voltage and current behavior across laser cavity and spark gap are simulated. The air is used as a lasing medium, as it contains 78% molecular nitrogen. The L-shaped electrodes are used as a cavity in the construction of this N_2 laser system. An ignition system in the form of the low inductance spark gap is built using the two bolts. Generally, the current passes through gas either by transverse or longitudinal discharge; in this work, the transverse discharge technique is used. Nitrogen laser produces a beam with a center wavelength of 337.1nm. Laser-induced fluorescence spectrum of the Pyranine is taken which shows its fluorescence in the green region with a maximum peak at the wavelength of 567.5nm. Pyranine is made up of a mixture of $C_{16}H_7Na_3O_{10}S_3$ so some other peaks can also be seen in the fluorescence spectrum with low intensity.

Keywords: Zemax, Irradiance, Laser-Induced Fluorescence, Pyranine, Blumlein

1. Introduction

The laser is the second half of the last century's groundbreaking invention. The laser is a successful offspring of optics and electronics. The landmarks in laser history date from 100 years ago when Einstein in 1917 predicted the idea of stimulated emissions. This idea helped the scientists understand lasers' concept, which Theodore Maiman of Hughes Research Laboratory led to creating the first laser using Ruby crystal called the Ruby laser in 1960. After that, in 1961, Ali Javan, W. Bennett, and D. Harriott (Bell Research Laboratory) developed the first-ever gas laser named He-Ne laser, a continuous wave laser, then Heard developed the first nitrogen laser in 1963 [1]. It showed paths to many laser developers to develop gas lasers.

Many scientists then worked on increasing the peak power output and energy of nitrogen lasers. Leonard developed the first TEA nitrogen laser in 1965 [2]. In 1967 John D. Shipman Jr. developed the TEA nitrogen lasers with parallel transmission lines [3]. Bergmann, in 1977 created a nitrogen laser at 20KV of 0.5MW peak power and energy of 630uJ per pulse [4]. Likewise, many scientists then developed nitrogen lasers and worked on improving their efficiency. Afterward, many applications were studied using nitrogen lasers to visualize the pulsed plasma in the range of nanoseconds by M. S Averin in 2004 [5]. A. S Provorov and co-workers in 2005 studied nitrogen laser applications in medicine [6]. The laser has developed in almost every field of life and contributes to a wide range of military, pharmaceutical, industries, and academic research applications.

This article is constituted as followed: the working principle of the Blumlein circuit and simulations are discussed in section 2. The design simulation of the nitrogen laser cavity is explained in section 3. Layout and detail fabrication of TEA N_2 laser are explained in section 4. Design, simulations and fabrication of high-tension pump source are reported in section 5. Characterization of the TEA N_2 laser system and LIF of Pyranine are explained in section 6.

2. Blumlein Discharge Circuit

The Blumlein discharge technique [7-9] is widely used to generate a discharge that results in lasing. Because of its low cost and ease of construction, it is widely used. In this technique, electricity is generated using a high voltage power supply and then quickly discharged through a switch, which in this case is the spark gap. The nitrogen laser's performance is strongly dependent on the type of electrical device used for discharge; the Blumlein discharge electrical system is used to deliver high voltage pulses. It is a pulse-forming network that can provide the required discharge to the cavity, resulting in excitation and the production of the laser. As a high population inversion is necessary for lasing, which in this case is produced by the Blumlein circuit, which stores energy and then leads to excitation [10, 11].

The Blumlein circuit is shown in Figure 1. The Blumlein system consists of two parts; the first part is the spark gap, which is used for the ignition of the whole system, which sparks when it reaches the breakdown level. In the second part, we have a laser cavity, which is formed by the two parallel plate capacitors, which are used for the energy storage purpose, and then there are two long electrodes that form the cavity in which lasing is produced and are arranged on top of the two capacitors and are connected through a resistor or inductor of specific value [12, 13].

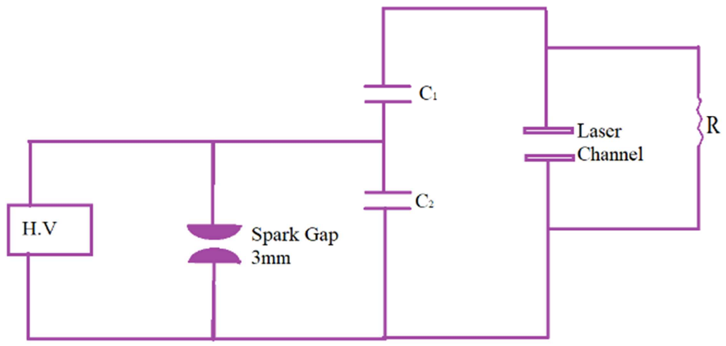


Figure 1. *Schematic of Blumlein discharge circuit.*

2.1. Current Behavior Across Spark Gap and Cavity (Resistors and Inductor)

Figure 2 shows the variation of current passing along the resistors and inductors of the spark gap and the cavity. As we can see from Figure 2, for the spark gap [red line], the current starts increasing, and after 500 us, it starts decreasing during that the gas discharge occurs in the laser cavity. Whereas in the case of the cavity [Blue line], one pulse decays in 500 us, and then the next pulse begins after that [13-15]. As resistor and inductor are in series so current behavior is the same across them.

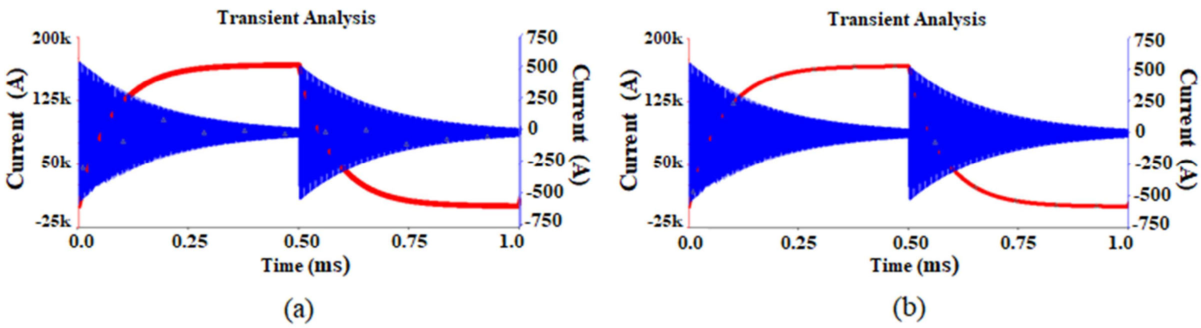
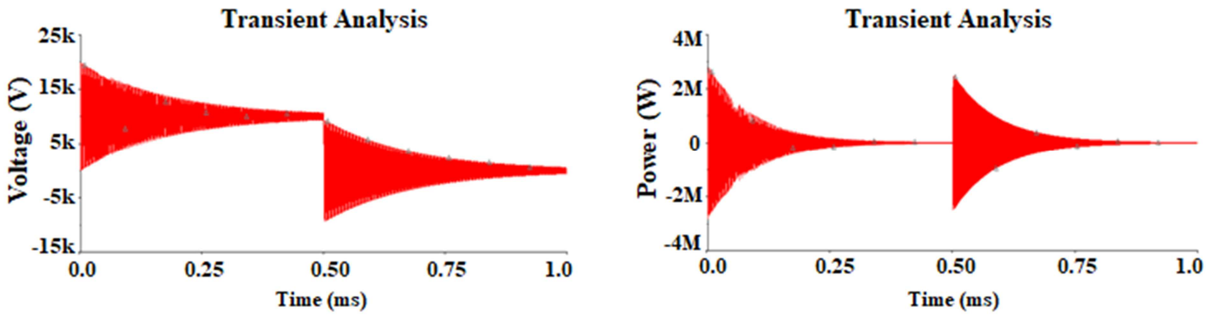


Figure 2. *(a) Current along time at Inductors (b) Current along time at Resistors.*

2.2. Voltage and Power Along the Cavity

The oscillatory behavior of voltage along time at the cavity is shown in Figure 3 given below, which is observed with a virtual oscilloscope in the Multisim software [16].



(a) (b)

Figure 3. *(a) Voltage variation across laser cavity (b) Power variation across laser cavity.*

In Figure 3(a), the graph shows that the voltage is supplied, discharge occurs; the voltage across the cavity reaches its maximum value and then starts decreasing with time; the magnitude of voltage falls to zero within 0.5ms.

The above Figure 3(b) shows the power variation in the cavity along time. As

$$P=VI \tag{1}$$

So power is directly proportional to the voltage across the cavity. When the voltage across the electrodes is maximum, then output power also increases with it and goes to a maximum value. As with time, the voltage decreases the power across the cavity also reduces. When the voltage across the cavity is less than the voltage's threshold value, then the output power is zero. When the next pulse appears, then voltage again goes to maximum, and power across the cavity also goes to maximum, and in this manner, this process continues [13, 17].

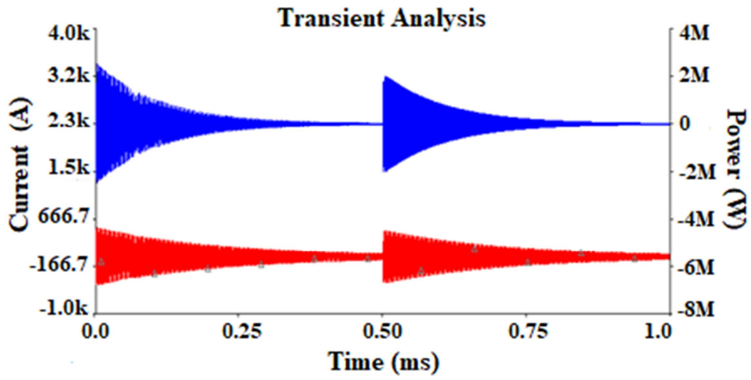
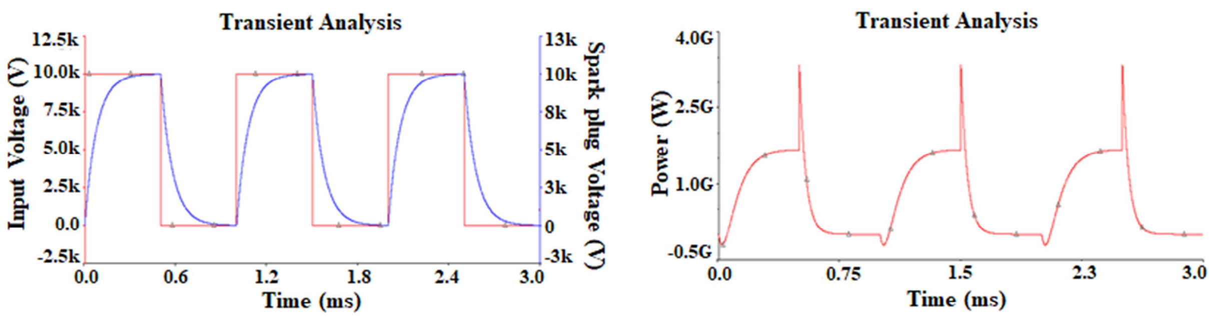


Figure 4. *Current [Red] and Power [Blue] variation along time.*

Figure 4 shows that power [blue] is greater than current [red], and power is increasing with the current. We can also see that power is always greater than current; the equation can explain this;

$$P = I^2 \cdot R \tag{2}$$

Where P is the power, I denote the current, and we can see clearly that power is directly proportional to the square of the current [18]. Power increases with the current, and power is always greater than current, consistent in above Figure 4.



(a) (b)

Figure 5. *(a) Continuous Voltage behavior along time at spark gap (b) Power behavior along time at spark gap.*

2.3. Voltage and Power Along the Spark Gap

Figure 5(a) shows the behavior of voltage across the spark gap [Blue] and the voltage applied [Red].

When the input pulse appears, the capacitor C_1 charges and then discharges through the spark gap, so the voltage across the spark gap increases with time. When the input pulse disappears, then the capacitor C_1 completely discharges through the spark gap, and then the voltage across the spark gap is maximum and, breakdown occurs in the spark gap. After that, the voltage across the spark gap decreases with time and goes to zero. Then the next input pulse appears, and again the capacitor C_1 charges and then discharges through the spark gap, and the voltage again starts increasing across the spark gap [13, 18].

3. Design and Simulation of Nitrogen Laser Cavity

3.1. Non-Sequential Component Editor

The design of the laser cavity is carried out using Zemax Optic Studio [19]. The non-sequential component editor window is used to define different parameters such as surface type radius of curvature, focal length etc. When all the surfaces are defined for all relevant parameters involved in the design, the software provides a 3D layout of the design (Figure 6). In the design, a fully reflecting mirror at one side of the cavity reflects the emitted photons and increases the output beam intensity. The focusing lens and detector are used at the output of the cavity to detect the beam and analyze it.

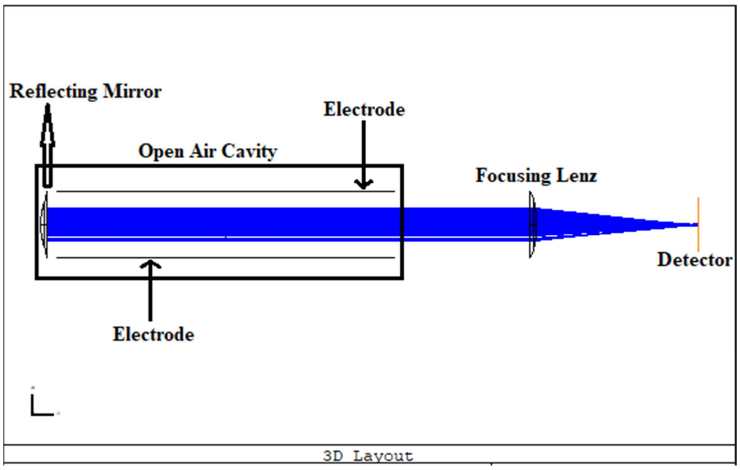


Figure 6. *3D layout of the designed N_2 laser cavity.*

3.2. Beam Size and Irradiance

The radiant radiation that a surface absorbs or the flux that is incident on the surface is referred to as irradiance. The irradiance is measured as power per unit area. Irradiance and distance have a direct relationship. Irradiance reduces as the distance between the radiation source and the detector rises. When large spaces need illumination, this is an important and valuable function of this measuring unit.

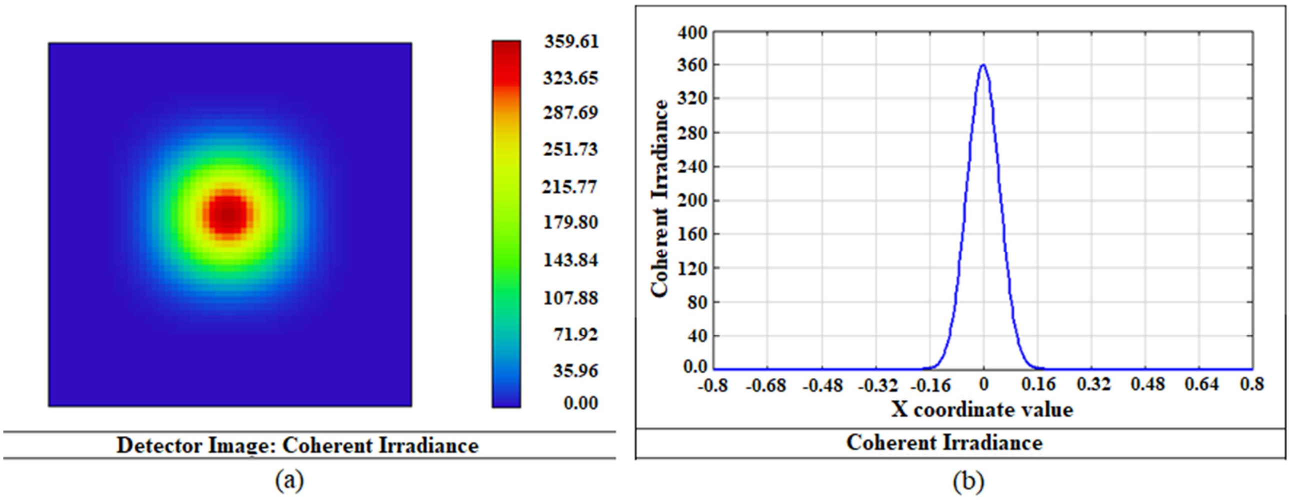


Figure 7. *(a) Total Irradiance and output beam spot (b) Irradiance along x-axis (X-cross) of output beam.*

Figure 7(a) shows the total irradiance plot and beam size. The red color indicates the highest irradiance (intensity) at 359.61 watts/square millimeter (Power = 10mW) and as the intensity decreases color changes to green and blue. The blue color indicates the lowest irradiance at 0 watts/square millimeter. This irradiance plot represents the top view of the Gaussian spectrum. Figure 7(b) shows the irradiance change along the horizontal axis (Y-center) of the beam. The peak irradiance appears at (0,0) coordinate with peak irradiance 359.61 watts/square millimeter. The irradiance (intensity) of the beam is high because there are no scattering and absorption losses in the cavity. The output beam is Gaussian with the symmetric irradiance distribution on both sides from the center of the beam [20, 21].

4. Layout of TEA N_2 Laser

TEA stands for, transverse electrical discharge at atmospheric pressure or Transverse excitation at atmospheric pressure. The nitrogen laser is designed using the TEA technique, which is somehow like those other scientists have explained [22, 23], but it differs in some respects like the length of the cavity, etc. The performance of nitrogen laser is influenced by many parameters, such as the voltage applied, the capacitor's storage capacity, inductance and impedance of the cavity, the length of the medium or cavity, the spark gap, and others. The design's core parts are the flat plate capacitors forming the transmission line, the two L-shaped electrodes forming the cavity, the resistor, and the igniting spark gap. The schematic of the design is given in Figure 8.

The cavity is open as air is the medium for lasing made up of two L-shaped aluminum electrodes arranged parallel to each other. Below the electrodes are the two capacitors of aluminum C_1 and C_2, which form the transmission line, and the electrodes are in complete contact with the capacitors. The spark gap is used here for the ignition purpose, connected to one of the two capacitors. A spark gap in a laser cavity is used to trigger the process and to excite the lasing medium in a period of a few nanoseconds. A variety of switches have been used, the spark gap switches [24], the thyratron type switches [25], and spark plug type [26]. A spark gap type switch is used in the design, which is simple, cost-effective, and the best means of switching. An inductor or resistor is used, which is connected to both electrodes, and its main work is to resist the change when there is a voltage breakdown in the system. As the power supply is switched on, the capacitors start charging, and the spark gap fires because of which the capacitor C_1 discharges, but the resistor opposes the discharge of capacitor C_2, and thus, a high potential difference is created between them. This high potential difference causes a strong electromagnetic field between the electrodes, which excites the air's nitrogen molecules and causes lasing when they de-excite.

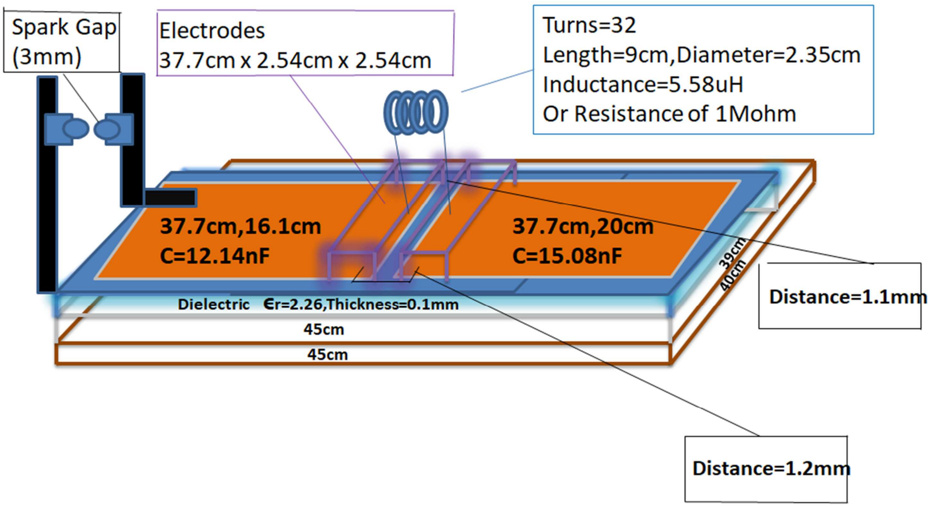


Figure 8. *Top view of the schematic of a Nitrogen laser.*

4.1. Fabrication of Capacitors

A wooden sheet of dimensions 45cm x 40cm is placed at the bottom, used as the ground. Above that, an aluminum sheet of 45cm x 38cm and thickness 1mm is placed on it, which is the groundsheet for both the capacitors. A polyethylene sheet of thickness 0.1mm is placed on the ground aluminum sheet and have a dielectric constant of $\epsilon_r = 2.25$. Two aluminum sheets of thickness 1mm and dimensions 37.7cm x 20cm, 37.7cm x 16.1cm are placed with 3mm distance between them on the dielectric, and in this way, two parallel capacitors are formed as C_1 and C_2. The capacitance of the two capacitors can be calculated as [27],

$$C = \frac{\varepsilon_r \varepsilon_o A}{d} \tag{3}$$

The area of capacitor C_1 is 606.97cm^2 (37.7cm×16.1cm) and of capacitor C_2 is 754cm^2 (37.7cm×20cm). Using these values in the above formula, the capacitance of capacitor C_1 is 12.09nF and, C_2 is 15.0208nF. The total capacitance of these two parallel plate capacitors is 22.1108nF. The capacitors must be in complete contact with the dielectric for smooth charging and discharging. Capacitors are used in this laser system for energy storage purposes. The capacitors store some amount of energy which can be measured from the relation,

$$E = \frac{CV^2}{2} \tag{4}$$

The energy stored in capacitors C_1 and C_2 is 1360.1mJ and 1696.5mJ respectively. Total Energy stored in capacitors,

$$E = E_1 + E_2 = 3056mJ$$

4.2. Fabrication of Laser Cavity and Spark Gap

The laser cavity is formed of two L-shaped aluminum electrodes. The electrodes are arranged on top of the capacitors so that they should bear the impact of heating and high voltage. The L-shape electrodes have dimensions of about 37.7cm×2.54cm×2.54cm. The length of the two electrodes is 37.7cm. The edges of the electrodes are made smooth to get a uniform discharge. The distance between the two electrodes at one end is 1mm, and the other end is 1.1mm. As per the need, distance is arranged according to discharge and can be increased or decreased using a non-conducting stick. The capacitors are held tight with the help of acrylic and wood sheets to prevent any gap between the capacitors and the dielectric. For the ignition of the laser system, a spark plug or a spark gap can be used, here a spark gap is used made from bolts having a round shape. One part of the spark gap is held on the smaller capacitor where the positive part of the power supply is connected, and the other part is held on the ground aluminum sheet where the ground terminal of the power supply is connected. The spark gap must be between 2-4mm; if it exceeds and the gap is too large, then the storage voltage will exceed the polyethylene dielectric's breakdown voltage and damage it. Hence, the system fails to perform, and if the gap is very small, it will also not provide lasing. Synchronize the spark gap with the cavity to make a stable system and get a smooth discharge in the laser cavity, and also set the spark gap according to the dielectric's breakdown voltage.

The two electrodes must be in contact through some DC path so that both electrodes charge up to the high voltage simultaneously; it can either be a resistor or an inductor connected between the electrodes. Resistance can be used in a range of 1kΩ to 1MΩ. The inductor coil is made of copper and is made by making 25 turns, having a diameter of 3cm and length of 12.2cm and have an inductance of 4.56uH, which is calculated using the formula,

$$L = \mu_r \frac{(turns)^2 (A)}{L} 1.26 \times 10^{-6} \tag{5}$$

The inductor and resistor provide a free path to the direct current, and the capacitors are charged, but when the spark gap fires and there is a large potential difference created, then the inductor opposes this change and stops the capacitor C_2 from discharging.

5. Design, Simulations and Fabrication of Electrical Pump Source

Nitrogen laser belongs to the gas lasers, which require electrical excitation for its pumping. The basic nitrogen laser need is to supply, a high electrical current with fast rise time and short pulses, to excite the gas molecules. The pump source is essential in the production of any type of laser. The pump source's main work is to excite some population for population inversion, leading to lasing through de-excitation. The voltage provided by the pump source should be so high that it exceeds the breakdown voltage of air, and the spark gap should start sparking, which results in a self-sustained streamer discharge [27, 28].

A high voltage pump source is the basic need for the TEA N_2 laser to excite the gas molecules. At the start, a low-tension power supply is created in the circuit diagram of this high-tension power supply. The low-tension part consists of a step-down transformer giving the output of 18V, which is then fed to the bridge rectifier, which converts the AC signal to DC. A smoothing capacitor is used to smooth out further the DC voltage, whose output is around 24V. This output is then supplied to the IC regulator LM7809, which regulates the output to 9V not to affect the other parts connected. The basic circuit diagram can be seen in Figure 9.

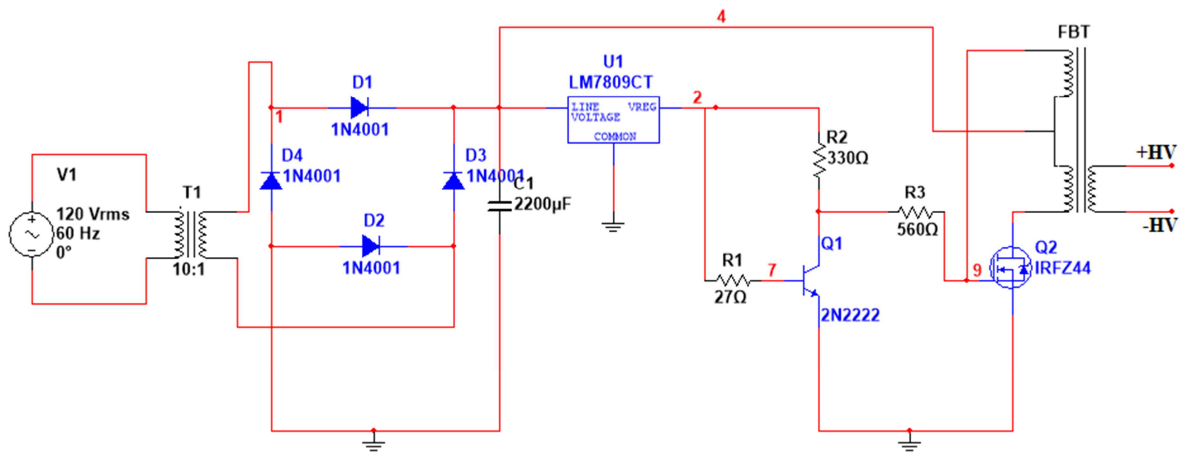


Figure 9. *Circuit Diagram of High-Tension Power Supply.*

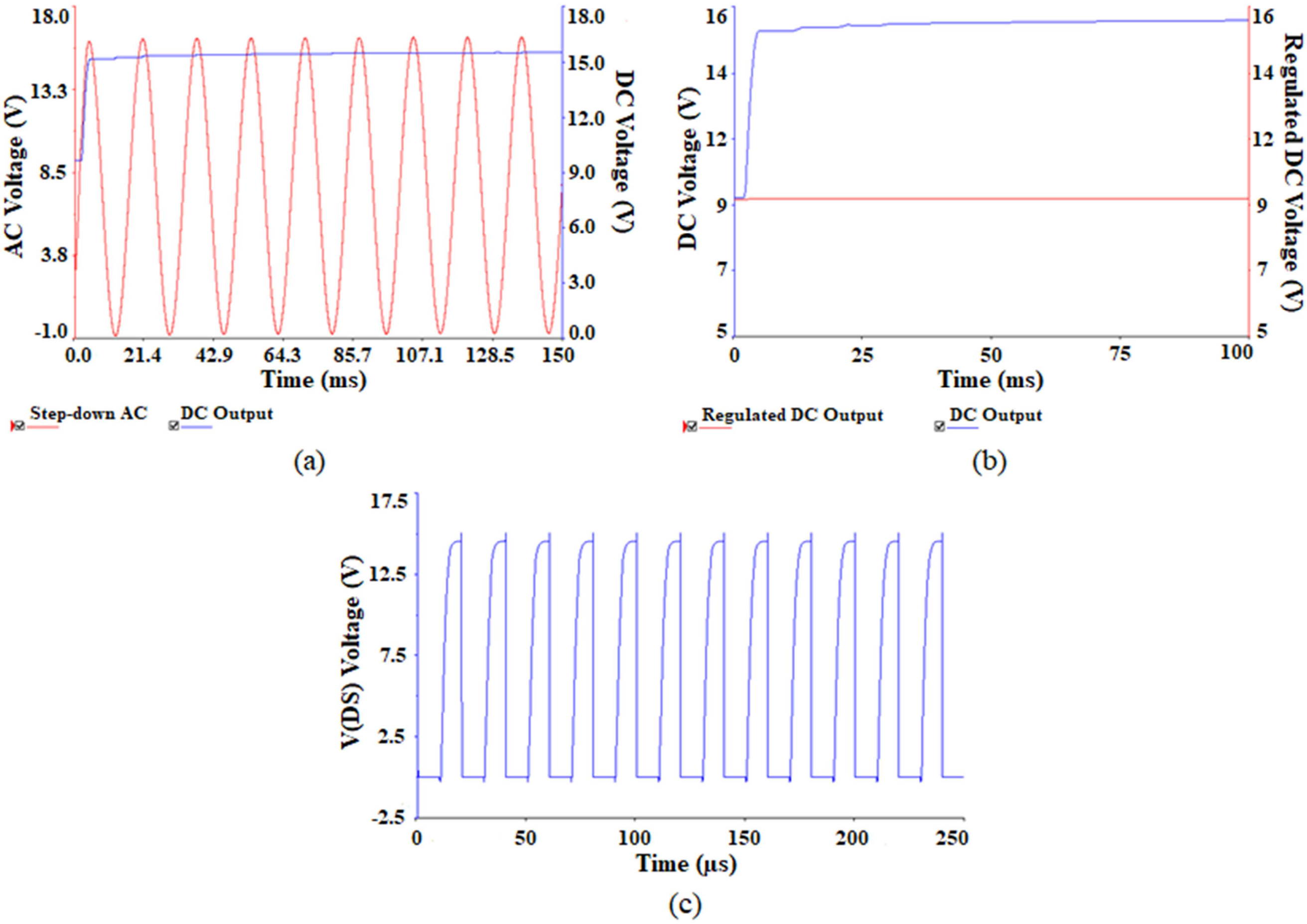


Figure 10. *(a) AC and DC output waveform (b) DC and Regulated DC output waveform (c) MOSFET behavior as a switch.*

The low-tension part's output is supplied to the flyback driver circuit, which drives the flyback transformer. We have a transistor, a MOSFET, and some resistances of specific values in the driver circuit. A transistor is a current-controlled device; it is a BJT (Bipolar Junction Transistor) that can be used as a switch or an amplifier, here it is used as a switch. The Emitter (E) of the transistor is grounded, the output of 9V is supplied to the Base (B) of the transistor, whereas collector (C) is connected to the gate of the MOSFET. The collector is nearly earthed when the transistor is saturated, and when switched off, the voltage of the collector increases to almost the same value as the voltage of the supply (Vs). Therefore, the waveform that occurs at the collector is in the form of a square wave.

MOSFET is a Metal Oxide Semiconductor Field Effect Transistor, which is being used for switching and amplifying applications. MOSFET is a voltage-driven transistor. MOSFET in this circuit is used for switching purposes with the transistor. IRFZ44N MOSFET is being used in this circuit, which is an n-channel MOSFET. It is used for low voltage and high switching speed applications. The source (S) is connected to the ground terminal and the drain (D) to the load. When it is in saturation mode, it supplies a burst of power to the Flyback Transformer. It works either in cutoff mode or saturation mode [29].

Parameters of Prototype TEA Nitrogen Laser are,

Table 1. *Parameters of Prototype TEA Nitrogen Laser.*

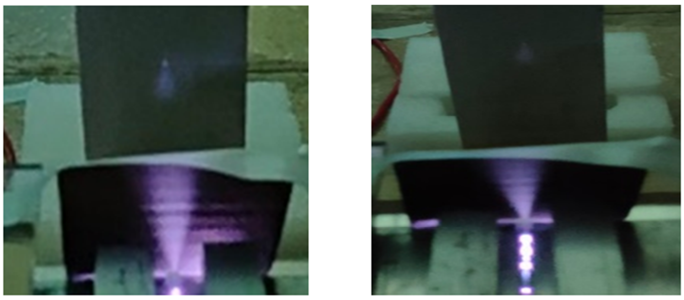
Active Medium	Air
Applied Voltage	15 kV
Pressure	1atm (760torr)
Beam Spot Color	Blue
Energy Stored in Capacitors	3056mJ
Spark Gap	Free Running

6. Measurement and Characterization

6.1. Output Beam Profile

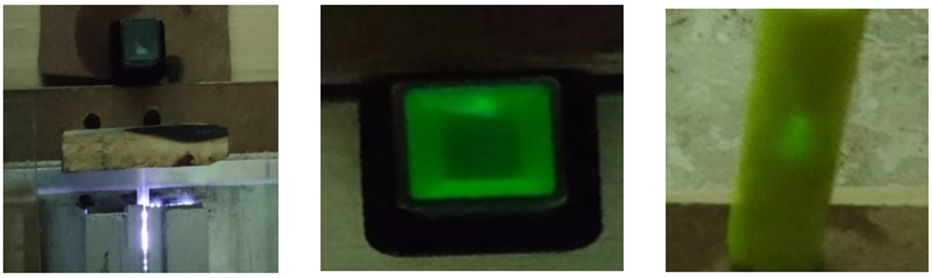
The beam spot fluoresces more on white than on yellow paper because when the laser beam falls on white paper its energy is high as its wavelength is low, but when the beam falls on the yellow surface it fluoresces into green and hence its energy is decreased. Spark gap separation has a clear effect on beam spot size, so spot size increases significantly as it is increased. Also, as the distance from the beam source is increased, the spot produces more fluorescence but with more divergence. The current along the cavity of the TEA Nitrogen laser is measured using an ammeter, a current of 50mA is flowing through the laser during the lasing process.

It can be seen in Figures 11 and 12 that the laser beam fluoresces more on white than on yellow. By increasing the spark gap separation, the beam spot fluoresces more, which shows its clear dependence on the spark gap separation, and can be seen in Figure 11 (a, b). Where the beam spot is more evident on white paper with spark gap separation of 3mm than the 2mm spark gap separation [30].



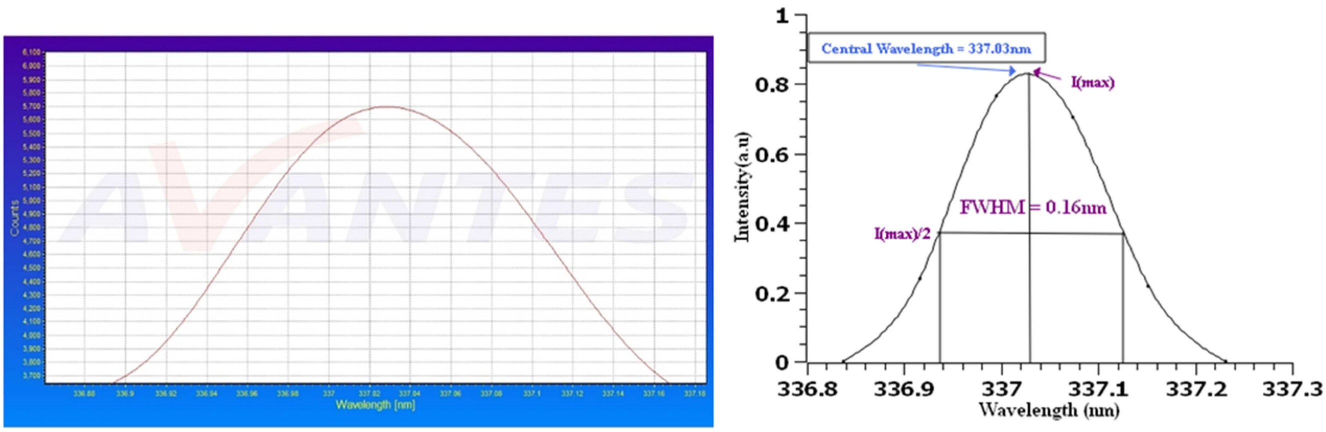
(a) (b)

Figure 11. *Beam spot on white paper (a) Spark gap separation of 3mm (b) Spark gap separation of 2mm.*



(a) (b) (c)

Figure 12. *(a) Laser beam in whitish liquid (b) Laser beam in a yellowish liquid (c) Beam spot on yellow surface.*



(a) (b)

Figure 13. *(a) Spectrum detected using spectrometer (b) Spectrum of TEA nitrogen laser with FWHM.*

6.2. Spectrum

The spectrum of the prototype TEA Nitrogen laser setup is taken using the Avantes Multichannel spectrometer [31] and then its data is again plotted by normalizing the data. We can see in Figure 13 the spectrum of the prototype TEA Nitrogen laser system showing its peak at 337.03nm with FWHM of 0.16nm. The spectrum is broadened because there is always broadening in a laser because of collisional or natural broadening mechanisms.

6.3. Laser-Induced Fluorescence Spectrum

Laser-induced Fluorescence [32] is a spectroscopic method in which an atom or molecule is excited to a higher energy level by the absorption of laser light followed by spontaneous emission of light. After some time, the excited species will usually emit light having a wavelength longer than the excitation wavelength in the order of a few nanoseconds to microseconds. Fluorescence occurs when high-energy photons are absorbed, and low-energy photons are emitted. Nitrogen laser has a wavelength in the UV region, as shown in Figure 13, so its energy is high compared to the visible region. A yellow highlighter ink mixed with water is used in a cuvette, which contains Pyranine, to see the fluorescent spectra and arranged the spectrometer detector after the cuvette.

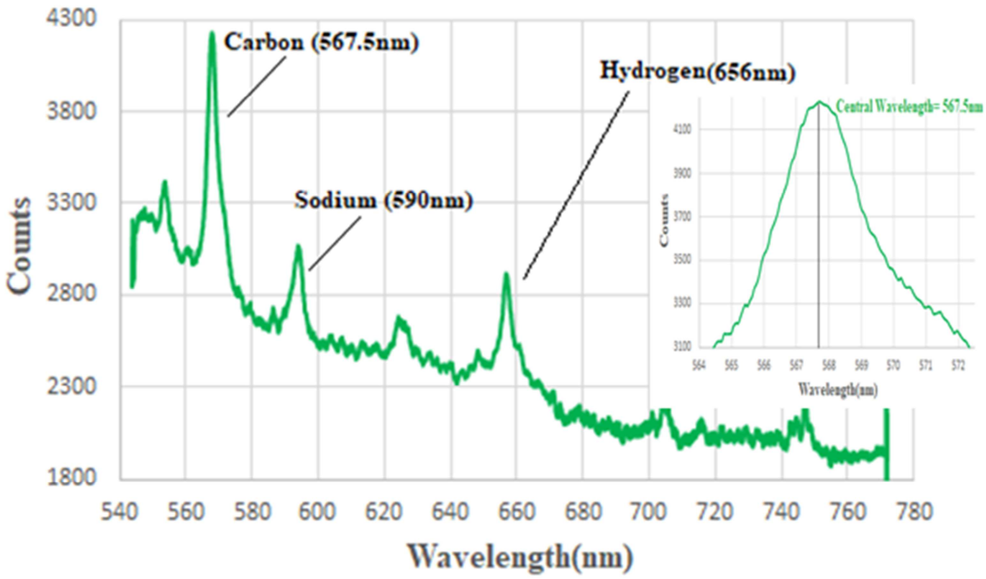


Figure 14. *Laser-Induced Fluorescence Spectrum (for maximum peak at 567.5nm: inset).*

Figure 14 clearly shows the emission of light in the visible green region. When nitrogen laser with 337.03nm wavelength falls on the cuvette, it absorbs the photon coming from nitrogen laser and gets excited to a higher energy level and then emits in the green region with a maximum peak at the wavelength of 567.5nm. Pyranine is made up of a mixture of $C_{16}H_7Na_3O_{10}S_3$ so some other peaks can also be seen in the spectrum.

7. Conclusion

The design and construction of a prototype TEA nitrogen laser with its high voltage power supply is carried out in this work. The high-tension pump source is designed and simulated using a flyback transformer. The laser cavity is designed and simulated by using the Zemax Optic Studio. The output can be viewed from both ends with one end being more efficient as initially the cavity is built without mirrors. A fully reflecting mirror is placed at one end to get a more intense beam from the other side. The spectrum is taken using the Avantes Multichannel spectrometer showing its center wavelength at 337.03nm with an FWHM of 0.16nm. The laser beam is observed on white, yellow paper and in whitish, yellowish liquid solutions showing fluorescence. It is observed that it fluoresces more on white paper. Laser-induced fluorescence is a technique in which high-energy photons are absorbed and low-energy photons are emitted. Laser-induced fluorescence is studied in which the spectrum is observed when nitrogen laser passes from the Pyranine solution and fluoresces to green by increasing wavelength with low energy.

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