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Design and Comparative Study of a one and Two Stage Blumlein Circuit TEA Nitrogen Laser

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Abstract: Two Prototypes of Transversely Excited at atmospheric pressure (TEA) Nitrogen laser systems (**One Stage Blumlein Circuit** and **Two Stage Blumlein Circuit)** were fabricated and operated. High voltage power supply with variable operating voltage (0-20 kv) and operating current (1-3A) was built and tested successfully. The gas flow rate of 15 L/ min and 10 L/ min for **OSBC** and **TSBC** was used. The performance of the fabricated systems was studied extensively reaching to the optimum operating conditions. The obtained laser output energy for the first system has linear relationship with the applied voltage. The maximum output energy was about (1.14 mJ) with (10.40) ns pulse duration and the half-wave divergence angle was about (0.1455 m rad). In the second system, the laser output energy has exponential relationship with the applied voltage; and the maximum output energy was about (10 mJ) with (8.20) ns pulse duration and the half-wave divergence angle was about (0.0582 mrad).

Keywords: *N_2 Laser, OSBC TEA N_2 Laser, TSBC TEA N_2 Laser.*

Introduction

An efficient operation of a transversely excited atmospheric (TEA) nitrogen (N2) laser usually requires ultraviolet (UV) preionization, and a fast discharge in the laser channel **[1, 2].** A fast discharge is often created using a parallel-plate Blumlein circuit while UV preionization of the laser channel is done. Critical circuit parameters such as, the inductance, capacitor ratio, plasma resistance, and spark gap inductance have strong effects on the laser performance [3].

A parallel-plate Blumlein circuit, owing to its low inductance, is commonly used for transversely excited atmospheric pressure nitrogen (TEA-N2) laser so that a large overvoltage is obtained in the laser channel prior to electrical breakdown **[4]**.

The main inductance in a parallel-plate Blumlein circuit is usually contributed by a spark gap, which is a convenient high-voltage switch for pulsed gas lasers. The circuit folding techniques can further reduce the circuit inductance but that of the spark gap remains largely unchanged **[5]**. In this case, an alternative to reduce the circuit inductance, and develop one stage Blumlein circuit (OSBC), TEA N2 laser was substituted by a two-stage Blumlein circuit (TSBC) for doubling the output energy of a TEA N2 laser **[6].**

In the present work, we report a fabrication and operation of two designed TEA nitrogen lasers, OSBC and TSBC. The main goal of this work is to compare two systems to reach to the best output operating parameters.

High Voltage Power Supply and TSBC Circuit Analysis

The drive circuit of the high voltage power supply used in the present work is shown in Figure 1. The design of the high voltage power supply consists of three stages, low power supply to provide +12 V dc voltages to operate timer circuit, and the flyback transformer driver which is based on MOSFET. The major electronic components in the driver circuit are LM555CM, 2N2222 transistor MOSFET IRF 540 along with the potentiometers, capacitor and resistances. C is the capacitance of the capacitor, which is 0.01 µF, and two variable resistors that have values which can be varied from 1 to 10 kΩ.

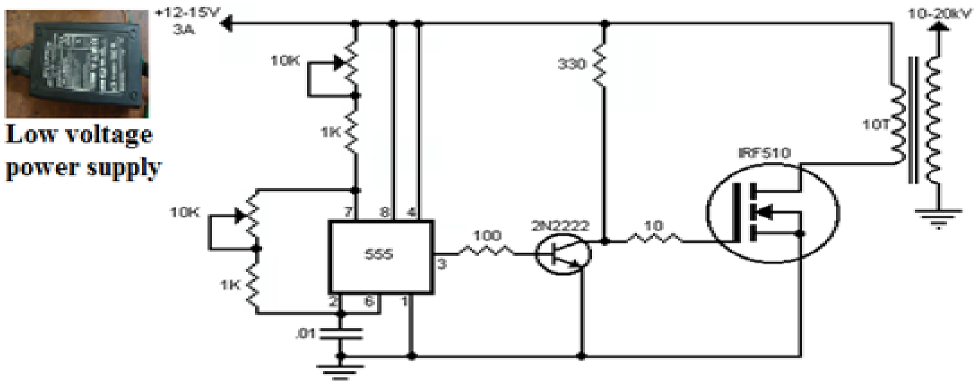

Fig. (1): High voltage power supply circuit diagram **[7]**

Two-stage Blumlein circuit shown in Figure 2 (a), has three time-delayed discharge loops as shown in Figure 2 (b) that can be described as follows: (a) C_d to the ground via the first spark gap, SG_1; (b) C_1 into C_d via the second spark gap, SG_2; and (c) C_2 into C_1 when the laser channel fires. The second spark gap, SG_2, while allowing the dummy capacitor C_d to switch to a negative voltage, delayed the discharge of C_1 into C_d. Upon C_1-to-C_d discharge, a fast voltage swing ramped up across the laser channel. The first discharge loop of C_d to ground remained in the reverse cycle which effectively enabled an overvoltage to be established across the laser channel **[6]**.

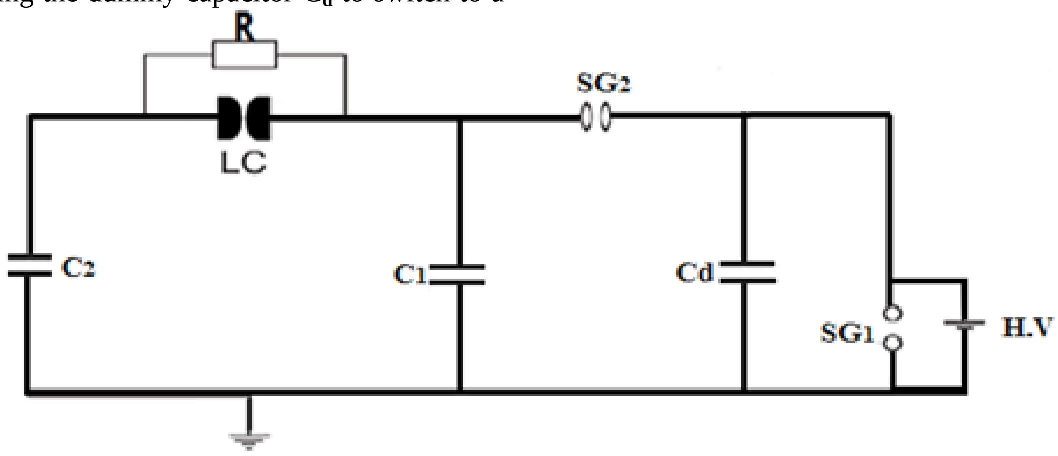

Fig. (2): (a) Two-stage Blumlein circuit TEA N2 Laser **[6]**

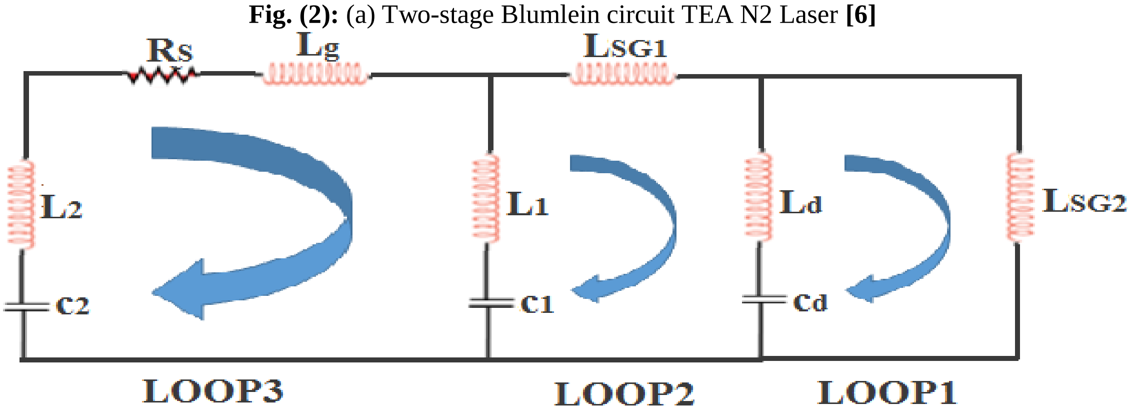

Fig. (2): (b) (TSBC) equivalent Blumlein line circuit **[7],** where:
Ld, L1, L2: are the parallel plate inductances
LSG1, LSG2: are the spark gap inductances
Lg, Rs: the laser channel inductance and resistance

High overvoltage was observed pre the electrical breakdown due to the emission from the SG_2, C_d, and the optimum delay of the breakdown in the laser channel was set at about 70 ns by varying the breakdown gap separation in SG**2**. We noticed from computer simulations of a discharge coupled circuit that the overvoltage across the laser channel reached a value of 1.92Vo and the peak discharge current by a factor of 2.3.

Figure 3 shows the time sequence of the breakdowns of the spark gap, SG**2**, and the laser channel with respect to the discharge current of the dummy capacitor via SG**1**. The laser channel current was measured and found to be increased by a factor of 2.4, which agreed with the predicted value of 2.3 **[8]**.

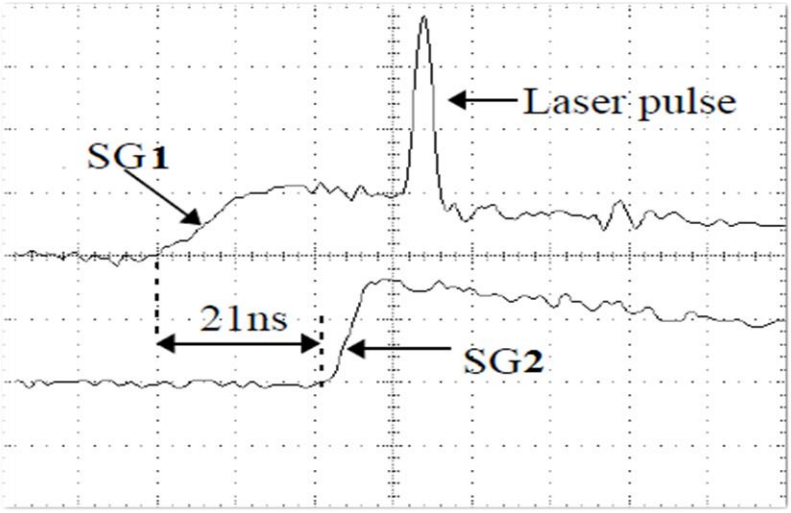

Fig. (3): Temporal characteristics and time delays between light emissions from the SG**2**, SG**1** and the laser pulse **[8]**

Experimental work

Measuring instrument

The TEA N2 LASER output energy for two systems under different condition was related to applied voltage, and gas flow rate was measured by (Gentec-EO energy meter).

The laser pulse shape and width were detected by a Thorlabs (**DET10 A/M**) output detector and analyzed on an Atten Electronics **(ADS1102CML)** digital storage oscilloscope rated at 200MHz. A set of pulses was displayed on the oscilloscope at different operating conditions

Laser output beam for the two systems was captured by a CCD digital camera (Sony group) at different distances from the laser setup for recording videos and converted to photoghraphs.

Design, Construction and Operation of the Two TEA N2 Lasers

The design of the first system is based on a traditional blumlien circuit named one stage blumlien circuit, and the second system is based on upgraded blumlien circuit named two stage blumlien circuits. The fundamental parts included in this circuit are:

- *Parallel plate capacitors*
- *Electrodes*
- *Spark gap*
- *High voltage power supply*

The parallel plate capacitor in was fabricated based on double side FR4 (PCB) Printed circuit board of dimensions (30cm×60cm), (PCB) which are used in nearly all modern electronic devices. The capacitors for the first system (One stage Blumlien) formed by removal of Copper thin layer from the lateral end of the plates in two sides of the board incremented by 1 cm, and removal of Copper thin layer incremented by 2 cm in one side from the center of the board. To be in this process, two capacitors were connected in parallel in dimensions (28cm ×28cm) for each capacitor.

The capacitors for the second system (Two stage Blumlien) were formed by the removal of Copper thin layer from the lateral end of the dimensions in two sides of the board incremented by 1 cm and by the removal of Copper thin layer incremented by 2 cm in one side from the two areas of the board. In this process, three capacitors of dimensions (22cm×14cm) were connected in parallel as shown in Figure 4 (a, b). This arrangement for OSBC formed the parallel combination of the two capacitors C_1 and C_2. The total capacitance of this combination is $6.44nf$, and for TSBC, the total capacitance is about$7.42\ nf$.

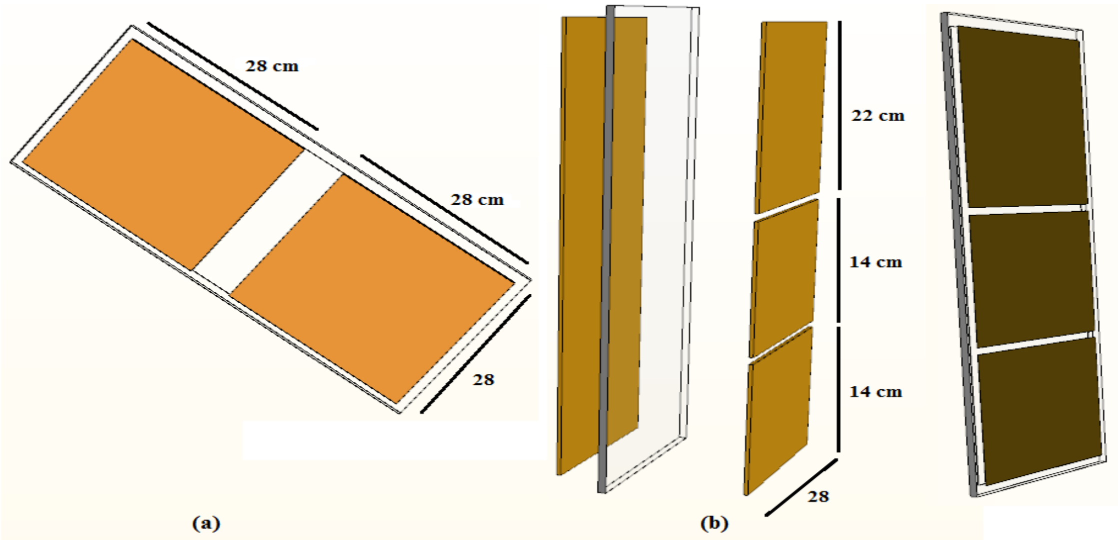

Fig. (4): (a) One stage Blumlien capacitor process (b) Two stage Blumlien capacitor process

In our work, the electrodes are manufactured for two systems depending on brass plates. These electrodes, shown in Figure 5, were shaped out of the edge of two brass plates: 25 cm long, 6 cm wide and 1.6 cm thick. After that, the formation for each one of them in a semicircular diameter cross section of 4 × 4 mm^2 was achieved.
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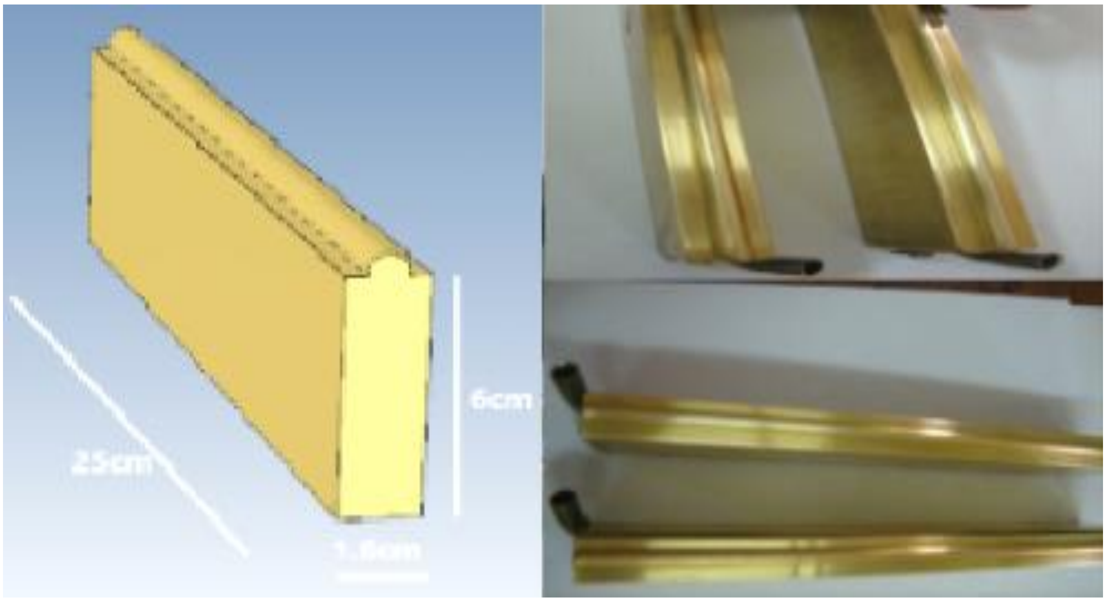

Fig. (5): Electrode configuration of TEA N2 laser systems

Two free running sparks gaps were fabricated have two electrodes for the One and Two-Stage Blumlien circuit. The two spark gaps have the same design approximately. The first electrode was designed and machined from brass plate with a semi-circular configuration in a diameter of (2.5cm) for the first, and the second spark gap and the second electrode. We used a spark plug as a second electrode for two sparks gaps as shown in Figure 6 (a, b) respectively.

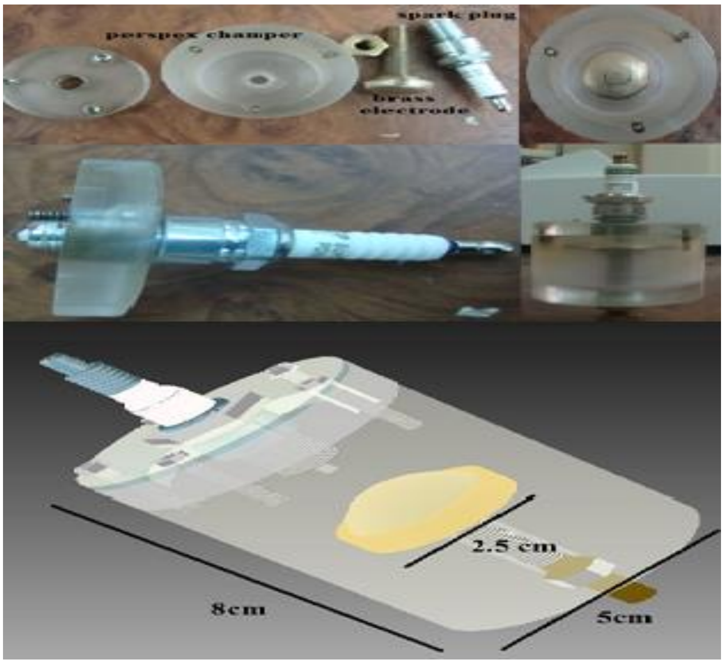

Fig. (6): (a). First spark gap configuration

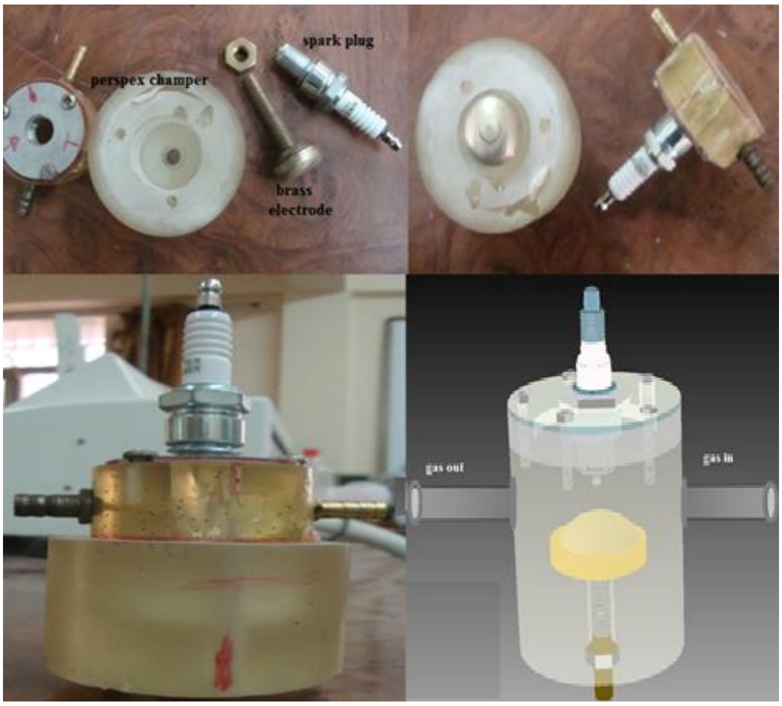

Fig. (6): (b). Second spark gap configuration

The electrode and parallel plate capacitors of the two systems are assembled using Perspex plate of dimensions (35 cm ×14 cm × 2cm). Figure 7 (a, b) shows the process of assembling the two systems.

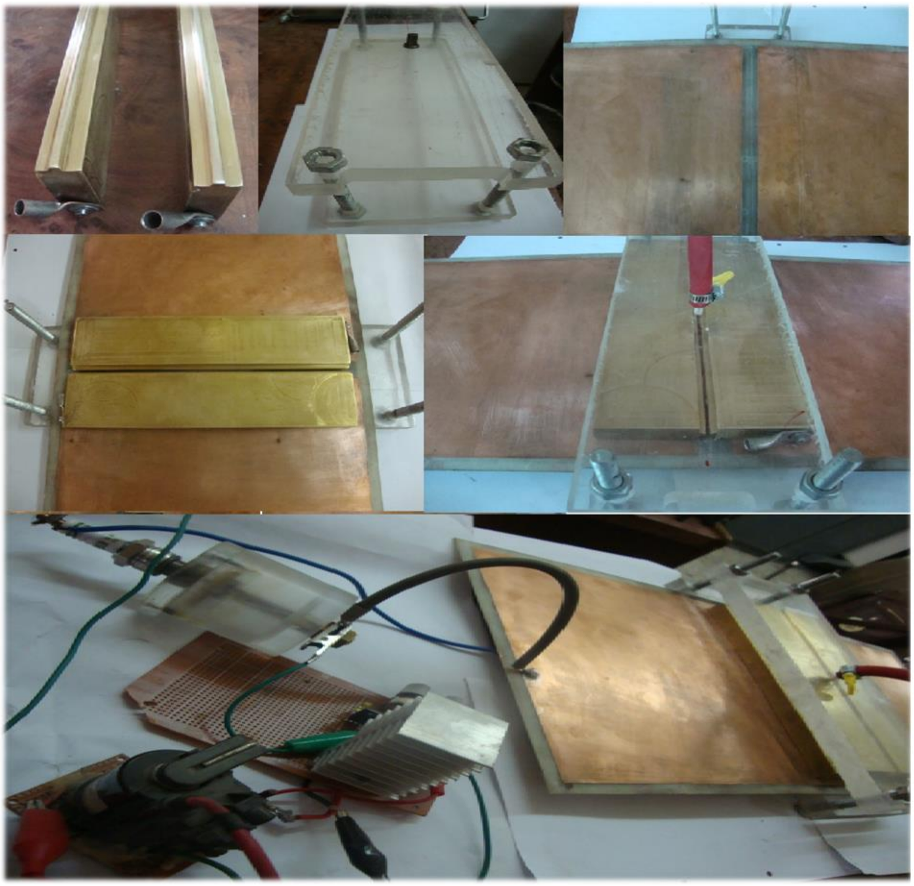

Fig. (7): (a). One stage Blumlein TEA N2 Laser system

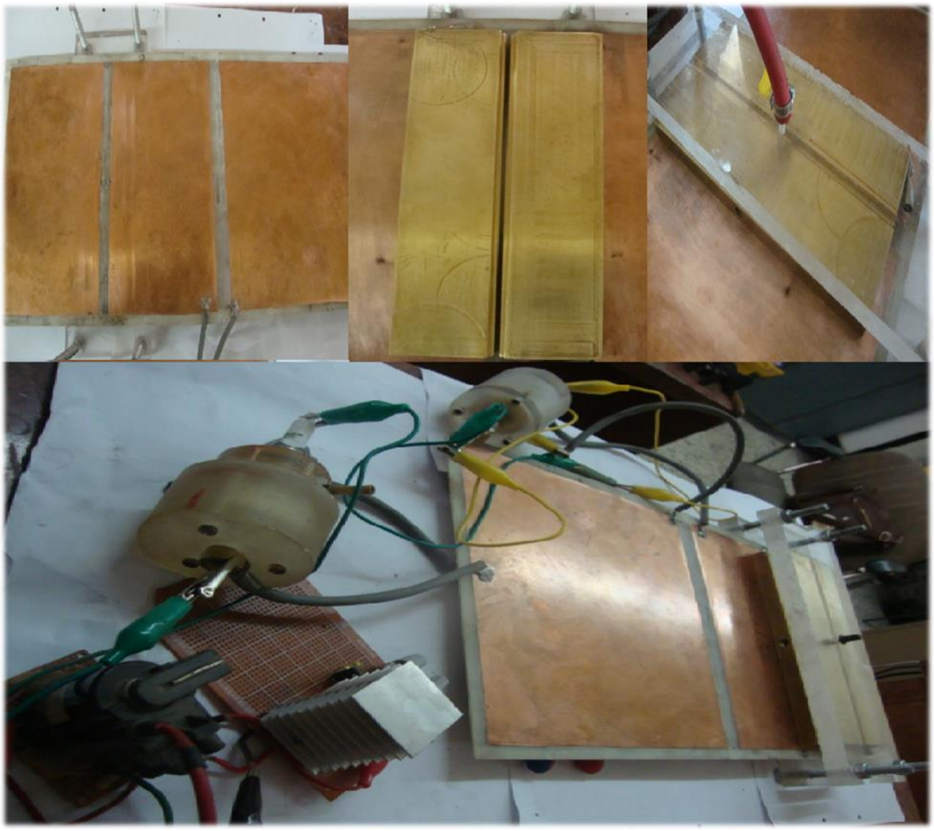

Fig. (7): (b). Two stage Blumlien TEA N2 Laser system.

Results and Discussion

Laser Output Energy

The laser output energy is at 3 mm distance separation between spark gap electrodes. Total capacitance is about ($6.44nf$), and applied voltage ranging of (10-20 kV) and gas flow rate at range of (5-20 L/min). The minimum and maximum output energy for OSBC is about 167.1 µJ and 1.14 mj, respectively. The minimum and maximum output energy for TSBC are about 266.3µJ and 10 mJ, respectively at 2 mm distance separation between first spark gap electrodes; (1mm) gap separation between second spark gap with total capacitance is about ($7.42\ nf$). Applied voltage ranged between (10 and 20 kV), and gas flow rate was at a rang of (5-20 L/min). A graph is plotted in excel software between output pulse laser energy and the voltage applied for two systems as shown in Figure 8 (a, b), respectively.

It is predicted that for OSBC the optimum value of energy increased with the increasing of voltage in a linear relationship with the best fitting equation ($E = 93.313V - 843.23$)**.** This behavior is in a good agreement with that recorded by Weefong KAU et al [9], and for TSBC in a third order polynomial relationship with the best fitting equation ($E = 0.0036V^3 + 0.1372V^2 - 0.8065V + 1.506$)**,** from Figure 8 (b) where the input voltage up to 17 kV, the behavior is linear after that for higher operation voltage. The output energy almost tends to saturation. This behavior is in a good agreement with that recorded by P. Richter et al [10].

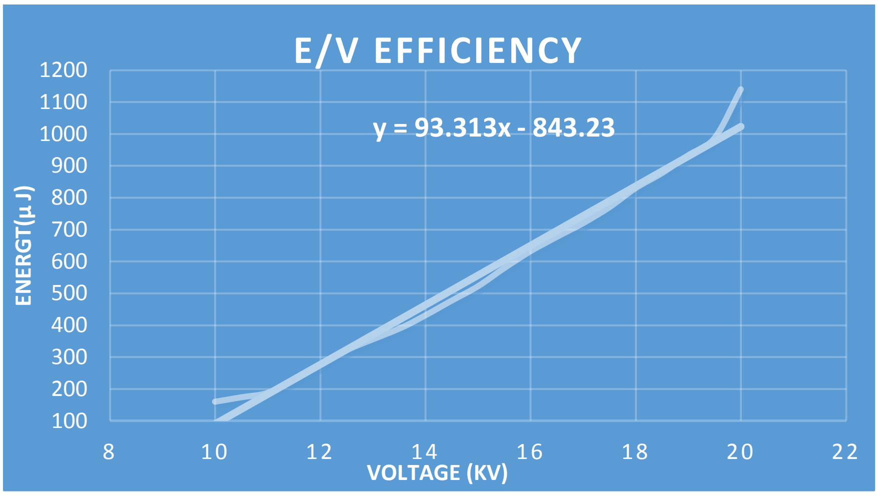

Fig. (8): (a). Variation of the output pulses laser energy with applied Voltage with a linear relationship empirical formula for OSBC system.

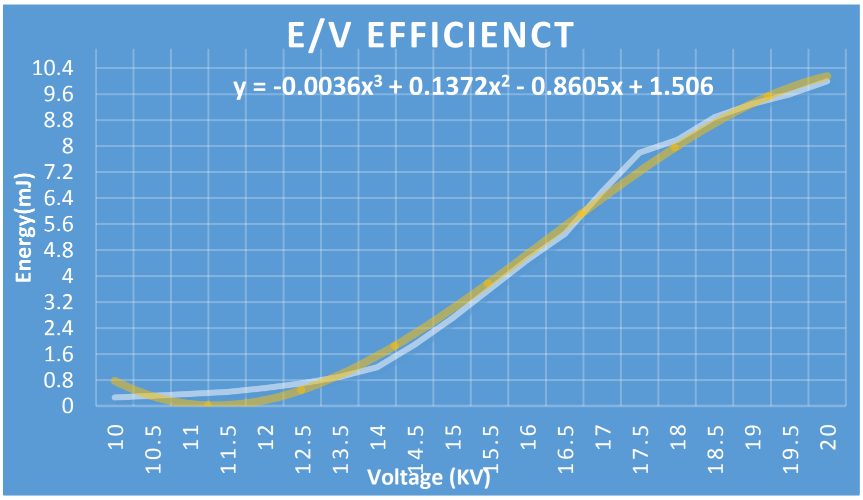

Fig. (8): (b). Variation of the output pulses laser energy with applied Voltage a third degree polynomial relationship empirical formula for TSBC system.

As the applied voltage increased, the strength of the electric field in the laser cavity increased. Due to which, energy of the electrons increased. These high energy electrons collide with the Nitrogen molecules and create the population inversion. As energy increased, the rate of collision increased. Therefore, population inversion builds up rapidly**.** We show the increase of output energy achieved by (TSBC) TEA N2 Laser system compared with an (OSBC) in the same range related to increasing applied charging voltage and for the same gap laser electrode separation which was set to a 3mm. A data of output energy for the two systems are plotted to show the increasing output energy for (TSBC) system as shown in Figure 9.

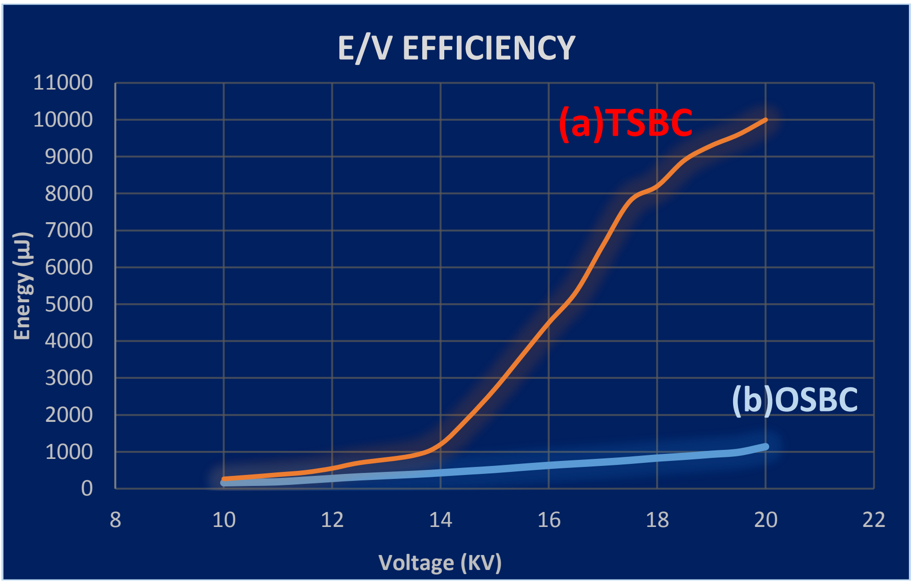

Fig. (9): E/V Efficiency compare (a) (OSBC) TEA N2 LASER system(b) (TSBC) TEA N2 Laser

Laser Pulse Shape and Width

The laser pulse shape and width for two systems at 20 kV charging applied voltage and 5 mm gap separation between laser electrodes. For OSBC**;** (3 mm distance separation between spark gap electrodes, 15 L/min gas flow rate). For TSBC (2mm) distance separation between first spark gap electrode, and (1mm) gap separation between second spark gap electrodes, 10 L/min gas flow rate) was recorded as shown in Figure 10 (a, b) respectively. For OSBC from Figure 10 (a), it is clear to us the laser pulse width is about 10.40 ns at FWHM and the rise time is 6 ns and for TSBC, from Figure10 (b), it’s clear that the laser pulse width is about 8.20 ns at FWHM and the rise time is 6 ns.

The constant value of rise time in spite of the folding of the capacitor discharge refers to the fact that total inductance was dropped by some factor of which the capacitors increased and more delay time was in spark gap so the rise time was still constant. This technique provides high discharge energy with small rise time.

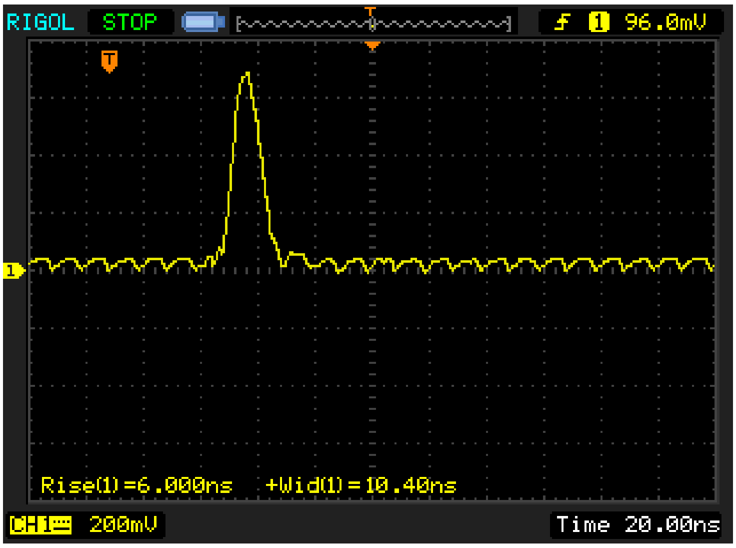

Fig. (10): (a). Laser pulse width and shape for (OSBC) TEA N**2** Laser system

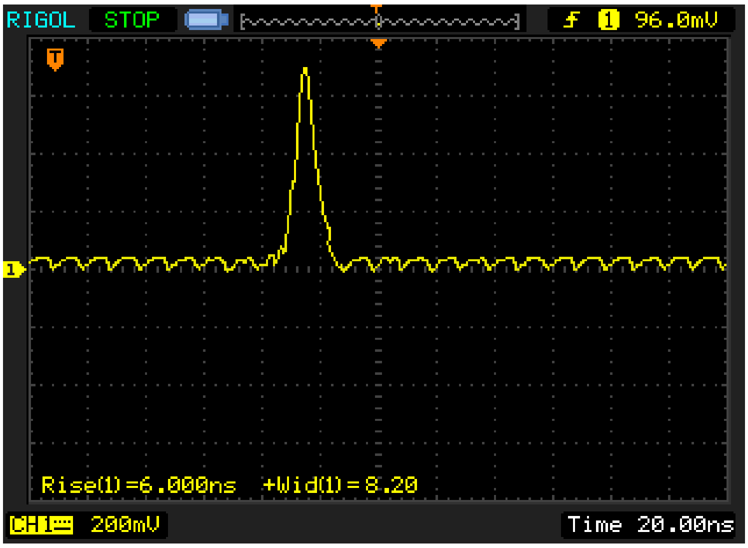

Fig. (10): (b). Laser pulse width and shape for (TSBC) TEA N**2** Laser system

We will explain the decrease pulse width for (TSBC) system. It was 8.20 ns compared with 10.40 ns for (OSBC) system, and this led to (TSBC) giving a higher laser power than (OSBC) system according to the experimental condition. From pulse duration for the two systems, we can calculate the laser peak power depending on the following equation:

$$Power_{\text{OSBC}} = \frac{E}{t} = \frac{1.14\times10^{-3}\,(J)}{10.40\times10^{-9}(S)} = 0.109\ Mwatt \qquad (4\text{-}1)$$

$$Power_{\text{TSBC}} = \frac{E}{t} = \frac{10\times10^{-3}\,(J)}{8.20\times10^{-9}(S)} = 1.219\ Mwatt$$

where:

E: Output energy of laser pulse for OSBC and TSBC TEA N2 Laser systems

t: Pulse duration for OSBC and TSBC of the discharge circuit

And also the total circuit inductance for the two systems is obtianed by using the equations (4-2):

$$T_{\text{OSBC}} = 2\pi\sqrt{LC}, \quad L_{\text{OSBC}} = 0.42nH \quad (4\text{-}2)$$

$$T_{\text{TSBC}} = 2\pi\sqrt{LC}, \quad L_{\text{TSBC}} = 0.23\ nH$$

Where

T: pulsed laser duration for OSBC and TSBC.

C: Total circuit capacitance for OSBC and TSBC.

L: Total circuit inductance for OSBC and TSBC.

We can notice that the TSBC has higher power, less pulse duration and less total circuit inductance compared with (OSBC)**.** A less total circuit inductance leads to increasing the efficiency of the laser system.

Laser Beam Profile

The images are observed which show the clear dependence of distance of focus point from the source. Figure 11(a) explains the spot size of a beam spot for OSBC on white paper when the distance from laser (20 cm) is 2.5 mm in a circular with ellipsoid shape, and the spot size of a beam spot at distance (50 cm) from laser source is 5 mm. Figure 11 (b) shows the width size of a beam spot for TSBC on white paper when the distance from laser (20 cm) is 3 mm in ellipsoid shape, and the spot size of a beam spot at distance (50 cm) from laser source is 4 mm and 5 mm at 75 cm from laser source.

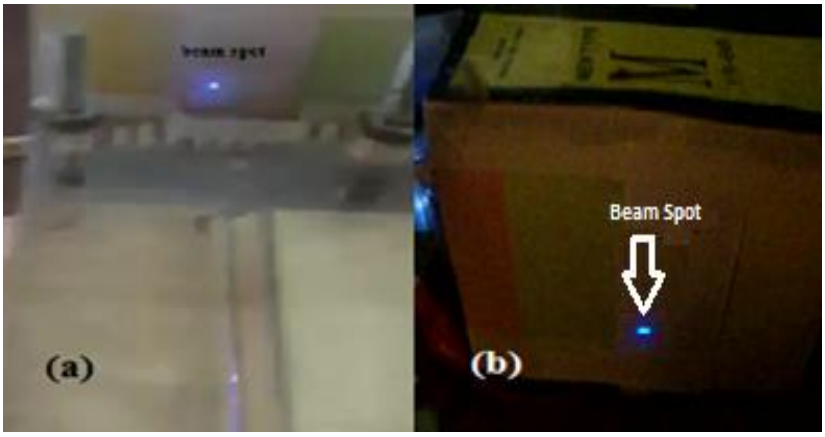

Fig. (11): Laser spot at 20 cm from the laser source for (a) OSBC (b) TSBC

It can be noticed that at the distance of 50 cm from laser source the spot width size is 5 mm for (OSBC) and it is larger than 4 mm for (TSBC) at the same distance and was equal to 5 mm for (TSBC) at 75 cm from the laser source. The laser beam divergence for two systems is calculated based on Equation (4-3):

$$\theta div_{\text{OSBC}} = \frac{\Delta x}{\Delta D} = 0.1455\, mrad \qquad (4\text{-}3)$$

$$\theta div_{\text{TSBC}} = \frac{\Delta x}{\Delta D} = 0.0582\, mrad$$

where:

X: Spot size on white paper for $OSBC$ and $TSBC$

D: Distance between laser source and white paper for $OSBC$ and $TSBC$

From this, we conclude that the (TSBC) has less divergence from (OSBC) at the same distance from the laser source and this is a very important advantage because of the large laser beam divergence and it is a problem in many laser applications.

Nitrogen lasers operate without mirrors, such lasers are called superradiant. The gain medium exhibits such high gain where spontaneous emission from nitrogen molecules at the end of the laser is amplified by the same group of nitrogen molecules in the tube, producing a usable output pulse in a relatively short path length. The gain for a nitrogen laser is on the order of 40 to 50 dB/m or more, depending on the specific laser [11], so in this work the (OSBC, TSBC) TEA N**2** Laser works without a resonator.

Laser Spot Intensity with Gas Flow Rate

The intensity of TEA N2 laser spot on white paper as a function of nitrogen gas flow rate was recorded. In the experiment, the gap separations between two electrodes was set at 5 mm. The operation of the laser was achieved for charging voltages at 20 kV and the separation between spark gap is 3 mm. The gas flow rate varied (5,10,15,20) L\min. The result was recorded by a CCD camera for recording videos and was converted to a picture which showed the image of laser spot on white paper (a) with nitrogen a flow rate of 5 L/min, (b) 10 L/min (c) and 15 L/min (d) 20 L/min. The N2 laser beam spot is significant and produces more fluorescence when it is exposed to a white paper [12].

It can be noticed in a Figure (12 (a)) for OSBC that the increasing intensity gradually from the state (a) to (c) and decreasing in the state (d) and in Figure (12 (b)) for TSBC, that the intensity gradually increased from the state (a) to (b) and decreased in the state (c). The laser intensity decreased because the velocity of nitrogen gas in the chamber increased and the position of nitrogen atom changed faster than before. This will affect the decreasing the interaction of the ionisation processes in gas discharge in the laser channel [13].

The maximum intensity on white paper for (OSBC) TEA N2 Laser occurs when N2 gas flow rate in laser channel is 15 L/min and when compared with (TSBC) system, the maximum fluoresces intensity on white is shown to be 10 L/min N2 gas flow rate. This is a very useful advantage because the amount of gas supplies into laser channel is one of the most important problems in TEA gas laser.

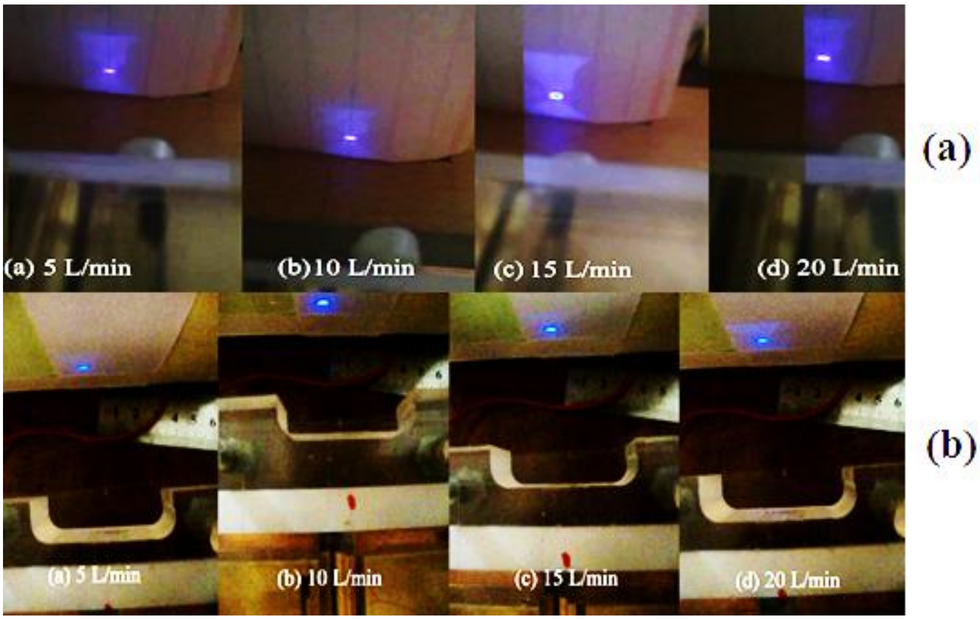

Fig. (12): The increasing intensity of the fluorescence on white paper at flow rate 5, 10, 15, 20 L/min, respectively for (a) OSBC TEA N2 Laser system (b) TSBC TEA N2 Laser system.

Conclusion

Prototypes of two designed TEA N2 Laser were fabricated and operated. Output laser energy is increased linearly for OSBC system and a third order polynomial for TSBC system with increasing applied voltage and with increasing gas flow rate. Duplication of the discharge Blumlein stage (TSBC) leads to forming more stability in laser discharge channel and this improves the laser output parameters.

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تصميم دائرة بلوم لاين في المرحلتين الاولى والثانية لليزر النتروجين ذي التهيج المستعرض تحت الضغط الجوي: دراسة مقارنة

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الخلاصة : تم تصنيع وتشغيل منظومـتين ليزر النتروجيـن، الأولى بمرحلة واحدة من دائرة البلوم لايـن والثانية بمرحلتـين من الدائرة ذي التهيج المستعرض تحت الضغط الجوي . وقد تم بناء مجهز قدرة عالي الفولتية بمدى متغير من 10 الى 20 كيلوفولت ومن 1 الى 3 امبير . كان جريان الغاز للمنظومة الاولى بحدود (15) لتر بالدقيقة و(10) لتر بالدقيه بالنسبة للمنظومة الثانية . تم دراسة اداء المنظومتين المصنعتين بعنايه وصولا الى شروط التشغيل المثلى، كانت اعلى طاقة طاقة خرج ليزري للمنظومة الاولى بحدود (1.14) ملي جول بزيادة خطية مع الفولتية الداخلة بأمد نبضة بحوالي (10.40) نانو ثانية وانفراجية للحزمة الليزرية تقريبا بحدود (0.1455) ملي راد بينما اعلى طاقة سجلت للمنظومة الثانية كانت بحدود (10) ملي جول بأمد نبضة (8.20) نانو ثانية وبزيادة للطاقة المستحصلة بعلاقة أسّية مع الفولتية الداخلة وبأنفراجية للحزمة المنبعثة حوالي 0.0582 ملي راد .