Simulation and Analytical Analysis of the Blumlein Discharge Circuit for the Generation of Coherent UV Pulses in Air

Muddasir Naeem[1], Rabiya Munawar[1], Mukhtar Hussain[1,2*], Tayyab Imran[1], Arshad Saleem Bhatti[1]
1- Department of Physics, Research Laboratory of Lasers (RLL)-Group of Laser Development (GoLD), COMSATS University Islamabad, Park Road, 45550, Islamabad, Pakistan.
2-GoLP/Instituto de Plasmas e Fusão Nuclear-Laboratório Associado, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal.
Email: mukhtar.hussain@tecnico.ulisboa.pt (Corresponding author)

Received: September 2020 Revised: December 2020 Accepted: February 2021

ABSTRACT:
Blumlein discharge circuit stores electrical energy in its transmission line and can release this energy within a few nanoseconds. This leads the Blumlein to discharge circuit for many applications ranging from electrical discharge in the air to generate nitrogen laser, excitation source for vapor lasers to sub-nanosecond avalanche drivers. In this letter, we have simulated the equivalent Blumlein discharge circuit in Multisimulation and compared the results with the analytical model to have the insight of variations of voltage, current and power in the Blumlein circuit. The Blumlein circuit is divided into spark gap (spark gap) and Blumlein transmission line sections to observe the voltage, current and power oscillations. The rapid oscillations of voltage across the spark gap initiate the discharge in the long transmission lines of Blumlein that generates the coherent UV pulses. This study could pave the way towards the generation of ultraviolet (UV) pulses in the air at the atmospheric pressure.

KEYWORDS: Blumlein Circuit, Blumlein Transmission Line, Multisimulation.

1. INTRODUCTION

A pulse forming network is the most important part for the discharge to occur, which is an electrical system that stores the electrical energy in the transmission lines. Then the stored energy is released in the form of short pulses, which are used for many pulsed applications. The best pulse forming network is the Blumlein, which was invented by Alan Blumlein, a British engineer in 1941 [1]. The essential part of producing a very high voltage for pumping gas lasers is to initiate the electrical discharge in the gas medium. Blumlein discharge circuit is one of the excitation techniques that is efficiently being used for the excitation of gas lasers, particularly ambient nitrogen or air. Blumlein discharge circuit is given preference over the other transmission circuits, owing to its short current rise time. The performance of the nitrogen laser is determined by the type of electrical discharge system used to create discharge proceeding to a laser. W. A. Fitzsimmons in 1976 [2], constructed nitrogen laser using Blumlein discharge and the capacitor-to-capacitor (C-to-C) discharge technique. In this study, the comparison of electrical and optical properties of both techniques are reported and it is concluded that Blumlein discharge technique is more efficient over C-to-C. In Blumlein, the discharge in the laser tube reaches to the peak value of V_0(Applied voltage) whereas in C-to-C the voltage is reached to only $\frac{V_0}{2}$.

H. Golnabi and A. Ashrafi in 1994 also studied the electrical properties of nitrogen laser constructed using Blumlein and C-to-C discharge circuits and concluded that Blumlein is more efficient [3]. Blumlein discharge circuit is employed to generate nitrogen laser at 0 to 5 bar pressure [4], and transversally electrical excitation at atmospheric (TEA) pressure nitrogen laser was reported [5,6,7,8]. Adolf J. Schwab in 1976 [9] presented the design of nitrogen laser using Blumlein discharge with the efficiency of 0.2-0.4% which is far better than that produced from C-to-C discharge system by K.A. Stankov with very low efficiency of 0.065% [10]. A detailed description on Blumlein discharge circuit, its resistance and inductance characteristics on the electrical discharge have been reported [11], [12].

Blumlein discharge circuit has many other applications. Luis L. Molina and co-workers used the Blumlein geometry for designing sub-nanoseconds

Paper type: Research paper
DOI: https://doi.org/10.52547/mjee.15.2.65
How to cite this paper: M. Naeem, R. Munawar, M. Hussain, T. Imran and A. Saleem Bhatti, "**Simulation and Analytical Analysis of the Blumlein Discharge Circuit for the Generation of Coherent UV Pulses in Air**", *Majlesi Journal of Electrical Engineering*, Vol. 15, No. 2, pp. 65-71, 2021.

avalanche drivers, in which by changing the Blumlein geometry voltage pulse amplitude and pulse width could be varied [13]. In 2009, Li Chen, with co-workers, used the Blumlein discharge circuit for excitation of He-$SrCl_2$ vapor laser [14]. In 1977, Ronal W. Waynant produced ArCl laser at 175nm using Blumlein discharge circuit for excitation [15].

Here, we have initially designed and simulated the Blumlein discharge circuit in the Multisimulation and observed the transient voltage and power oscillation across the various section of the Blumlein circuit. Later, we have employed the analytical model to explore the voltage oscillations in the Blumlein circuit and divided it into two sections: spark gap and Blumlein transmission line. We have compared the simulation results with the analytical modelling which agreed reasonably. This study could pave the way to build a Blumlein transmission line-based nitrogen oscillator and synchronized amplifier to generate efficient and coherent UV pulses for the spectroscopy applications at the newly built Research laboratory of Lasers (RLL).

This article is constituted as followed: the working principle of the Blumlein circuit is discussed in section 2. The equations of the analytical model are explained in section 2.1. The Multisimulation and analytical results are reported in section 3. Finally, the conclusion and outlook of this study are reported in section 4.

2. WORKING PRINCIPLE OF BLUMLEIN CIRCUIT

In the Blumlein circuit, the electrical energy is stored in the transmission line of circuit, and then rapidly discharged through a switch which in our case is the spark gap or Spark Gap (SG). Blumlein discharge technique is extensively being used to produce an electrical discharge in the laser cavity, which leads to lasing and is used widely because of low cost and easy construction. Blumlein circuit is a pulse forming a network which provides the needed electrical discharge in the cavity which is often formed by the series of parallel capacitors or Aluminium-based two parallel plate capacitors [6,7]

The basic schematic of the Blumlein circuit is shown in Fig 1 (a). The Blumlein system consists of two sections, and the first section is the spark gap which is used for the ignition of the whole system. The second section is termed as a Blumlein transmission line which is formed between the two parallel plate capacitors interconnected through a series combination of inductor and transient resistor. The equivalent circuit for Blumlein is shown in Fig1(b), section A consists of transient resistance R_1 and inductor L_1 connected in series to form a spark gap. Section B is the Blumlein transmission line consists of a parallel capacitors C_1 and C_2 forming the transmission line that are connected through transient resistance R_2 and inductance L_2.

Section A of the Blumlein circuit operates before and section B works after the electric breakdown at the spark gap, respectively. When the input of high voltage is supplied across the spark gap ends whose one end is connected to the common end of both capacitors while another end is connected to the C_1, the charging of both capacitors begun. Meanwhile, the potential difference builds up across the spark gap electrodes, as the potential difference exceed the limit of the threshold, the spark gap fired (electric breakdown). At this point, the C_1 discharge at once while the combination of R_2 and L_2 keeps the C_2 to highly charged. It creates a huge potential difference across the parallel plate's capacitors transmission line (laser discharge channel). As a result, an electric discharge occurred across the Blumlein transmission line. The electric discharge excited the air molecules (mostly N_2) and during de-excitation results, coherent UV pulses [2-8]. The behaviour of the voltage variation across the transmission line will be explained in section 2.

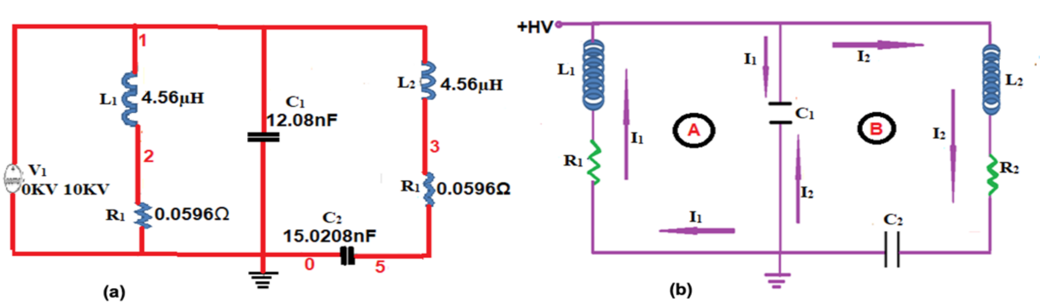

Fig. 1. (a)Simulated Blumlein circuit (b) The schematic of current flow in the equivalent Blumlein circuit (Section A & B corresponds to the free-running spark gap and Blumlein transmission line having current I_1 and I_2, respectively)

2.1. Transmission Line Equation and Boundary Conditions

An applicable transmission line equation for the voltage **V** and current **I** on a section of the transmission line of length at any time **t** are given by [16],

$$\partial V_i (x_i, t)/ \partial x = -L_i \{\partial I_i (x_i, t)/ \partial t\} \ldots\ldots \ldots\ldots\ldots\ldots (1)$$
$$\partial I_i (x_i, t)/ \partial x = -C_i \{\partial V_i (x_i, t)/ \partial t\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$
$$0 \le x_i \le l_i$$

L and **C** are the distributed inductance and capacitance per unit length respectively, and l_i is the total length of line section. The initial conditions are:

$$V_i (x_i, 0) = V_0 \quad I_i (x_i, 0) = 0$$

The boundary condition at the end of the spark-gap is:

$$V_1 (0_1, t) = -R_1 [I_1 (0_1, t)] + L_1/R_1 \{\partial I_1 (0_1, t)/ \partial t\} \ldots\ldots\ldots\ldots \ldots (3)$$

L_1 and R_1 represent the inductance and resistance of the spark gap. $I_1 (0_1, t)$ and $V_1 (0_1, t)$ are the current and voltage passing through inductance and resistance of spark gap, respectively.

The boundary conditions at the end of the Blumlein transmission line are:

$$V_1 (l_1, t) - V_2 (0_2, t) = L_2 \{\partial I_2(0_2, t)/ \partial t\} + R_2 [I_2 (0_2, t)] \ldots\ldots\ldots\ldots (4)$$
$$I_1 (l_1, t) = I_2 (0_2, t)$$

l_1 is the total length of the spark gap, L_2 and R_2 stand for inductance and resistance, $I_2 (0_2, t)$ is the current, and $V_2 (0_2, t)$ is the voltage at the edge of the Blumlein transmission line, respectively.

The boundary condition at the Blumlein transmission line is;

$$I_2 (l_2, t) = 0$$

The Blumlein transmission line impedance is not linear and must be treated as voltage-dependent. This nonlinear behaviour of the channel impedance makes it necessary, in the time development of solution of the partial differential **Eq. (4)** to distinguish between two-time intervals. Initially, only the spark gap is subjected to the dynamical changes, whereas the Blumlein transmission line remains in its initial state. In the second time interval, both the spark gap and Blumlein transmission line are time-varying. The subscripts S and L in the current, voltage, and lengths symbol are denoting the spark gap and Blumlein transmission line, respectively.

3. RESULTS AND DISCUSSIONS

3.1. Simulation and Analytical Modelling for Blumlein Transmission Line

The working principle of the Blumlein circuit is discussed in subsection 2. The two stages (**A** & **B**) are helpful to understand the behaviour of voltage and current evaluation in the Blumlein circuit. This behaviour of voltage and current at each point in the Blumlein circuit can be understood by using the Multisimulation software. The simulated Blumlein circuit is shown in Fig. 2 (inset). The spark gap and Blumlein transmission line have the transient resistance R_1, R_2 and inductance L_1, L_2, respectively. The values of resistance and inductance are kept the same for the synchronization of the Blumlein transmission line and spark gap.

The behaviour of voltage in the Blumlein transmission line and comparison of simulated (Multisimulation) and analytical model for voltage variation in the Blumlein transmission line are shown in Fig. 2 which agreed well to each other. The voltage increases to its maximum value within 0.5 µs and begins to fall after 0.75 µs (inset, Fig. 2(b)), this behaviour of voltage is consistent with results presented [17]. We have calculated the 3D voltage waveform in the cavity for 500 µs (Fig. 3(a)) and for one cycle (Fig. 3(b)) along the parallel plate transmission line of 32 cm length that exhibits the similar voltage variations as reported [18], [19].

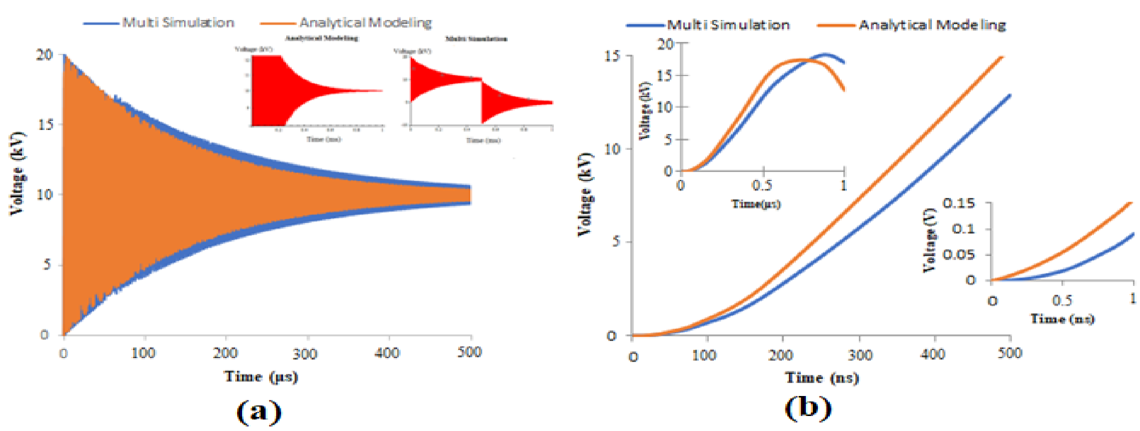

Fig. 2. Voltage variations in the Blumlein transmission line section (a) for 500 µs (for 1 ms: inset), (b) for 500 ns (for 1 µs, 1ns: inset).

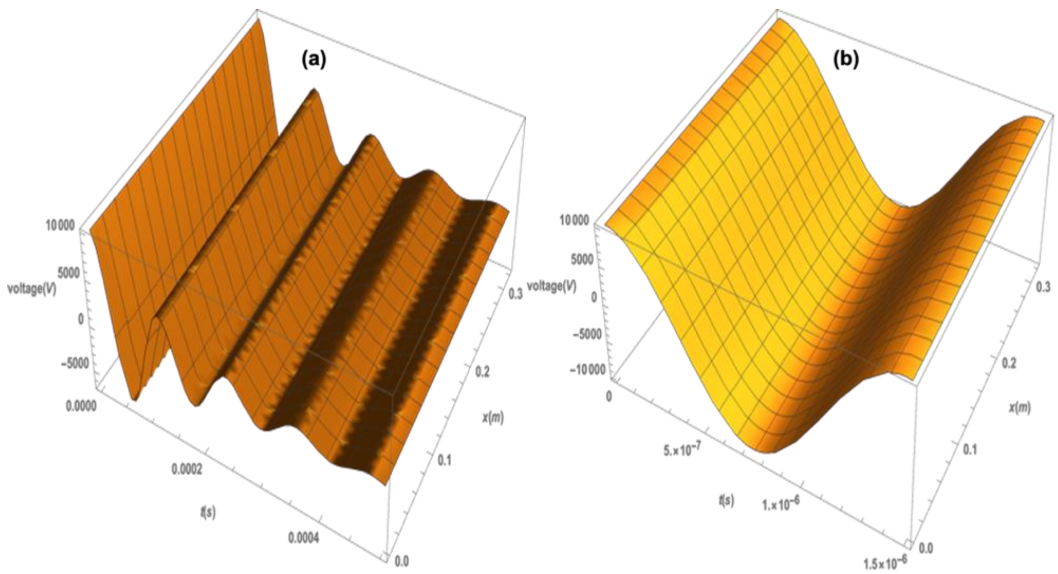

Fig. 3. 3D voltage variations in the Blumlein transmission line having a length of 32 cm, (a) for 500 µs, (b) for one cycle (1.5 µs).

3.2. Simulation and Analytical Modelling for the Spark Gap

The results of simulated and analytical modelling for the voltage and power variations along the spark gap are shown in Fig. 4. Initially, when high voltage is applied across the spark gap ends, it reaches to maxima within 250 µs which remains constant for next 250 µs and falls to minimum value within 100 µs as shown in Fig. 4. The power variation followed the same pattern as voltage. The analytical modelling depicts less value due to saturation. The 3D variation of voltage for 3 mm gap electrodes of a spark gap is shown in Fig. 5 for 500 µs (Fig. 5 (a)) and single cycle (Fig. 5 (b)).

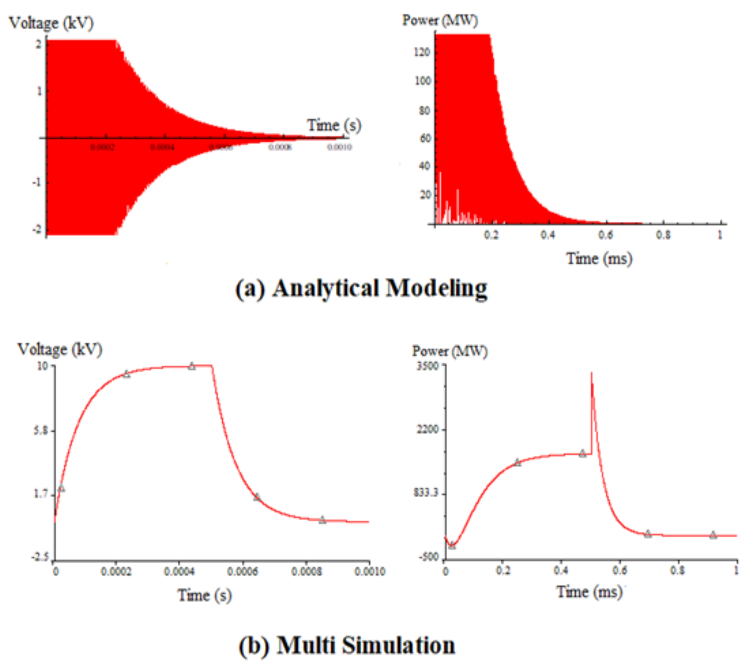

Fig. 4. Voltage and power variation in the spark gap section, (a) Analytical modelling (b) Multisimulation.

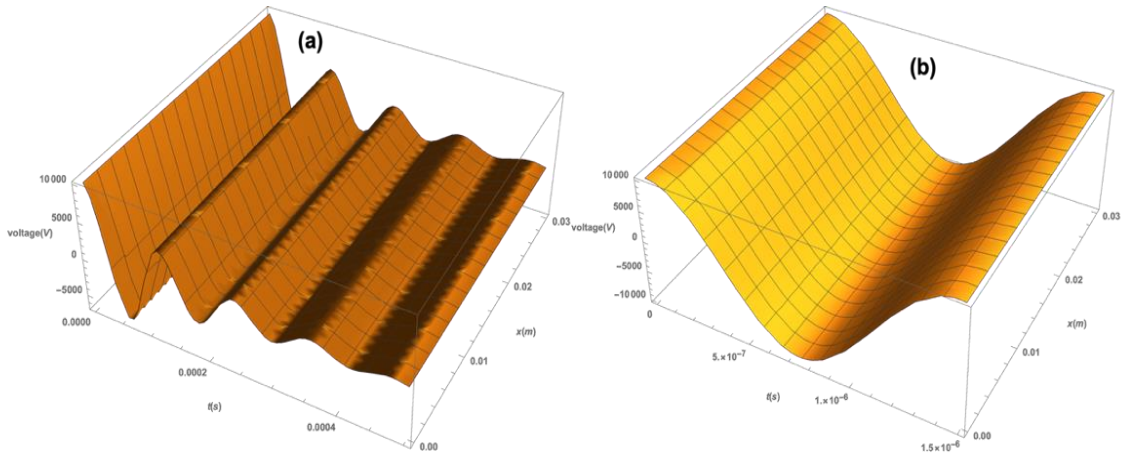

Fig. 5. 3D voltage variations in spark gap section of Blumlein transmission line having a length of 3 mm, (a) for 500 µs, (b) for one cycle (for 1.5 µs).

3.3. Transient Analysis of the Spark Gap

In this section, we present the transient analysis of voltage and power across the resistive components of the Blumlein circuit. The voltage variation across the resistors of spark gap R_1 is shown in Fig. 6 (a). Initially, when high voltage is applied across the ends of the spark gap electrode, the voltage between the spark gap builds up and reaches to the maximum value that is approximately 380 µs. It remains stable at next 100 µs and falls rapidly ~ 500 µs, as shown in Fig. 6 (a). This rapid fall of voltage occurred when discharge across the spark gap electrodes happened [4,5,8,20]. The spark gap operates at the repetition rate of 1 kHz. The electrical power variations across the spark gap are shown in Fig. 6 (b) for a single cycle. It shows that initially, the power across the spark gap is quite low, which reaches maximum value of 3GW after 500 µs that falls rapidly (within 100 µs). This behaviour of power is consistent with the voltage variation across the spark gap.

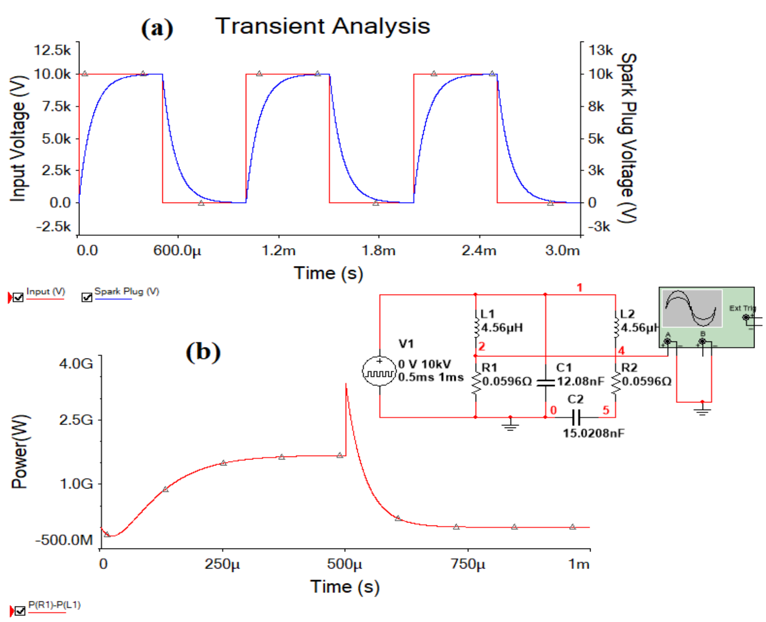

Fig. 6. (a) Variation of voltage across the spark gap (inset simulated circuit), (b) single-cycle power variation across the spark gap.

3.4. Transient Analysis of Blumlein Transmission Line

The transient analysis of voltage and power in the Blumlein transmission line is shown in Fig. 7(a) & 7(b), respectively. As the input voltage is applied, the voltage across the Blumlein transmission line increases and reaches to maxima within 1 µs, as shown in the inset of Fig. 7(a). The voltage drops to minima in 500 µs and changes the sign of voltage, which also has similar behaviour and reaches to minima after 500 µs as a shown inset of Fig. 7(a). This rapid oscillation of voltage creates a huge potential difference across the Blumlein transmission line transversely, which excites the air molecules that contains 78% nitrogen. On the de-excitation of nitrogen molecules when the potential difference drop to minima, emits the ultraviolet pulses. The electrical power variation across the Blumlein transmission line for 1 ms to 1 µs is shown in Fig. 7(b). The electrical power across the Blumlein transmission line reaches to 6 MW and exhibits the oscillatory behaviour. During this rapid oscillation of electric power in the Blumlein transmission line, the successive pulses of coherent UV are generated and famously known as TEA N_2 laser [5-8].

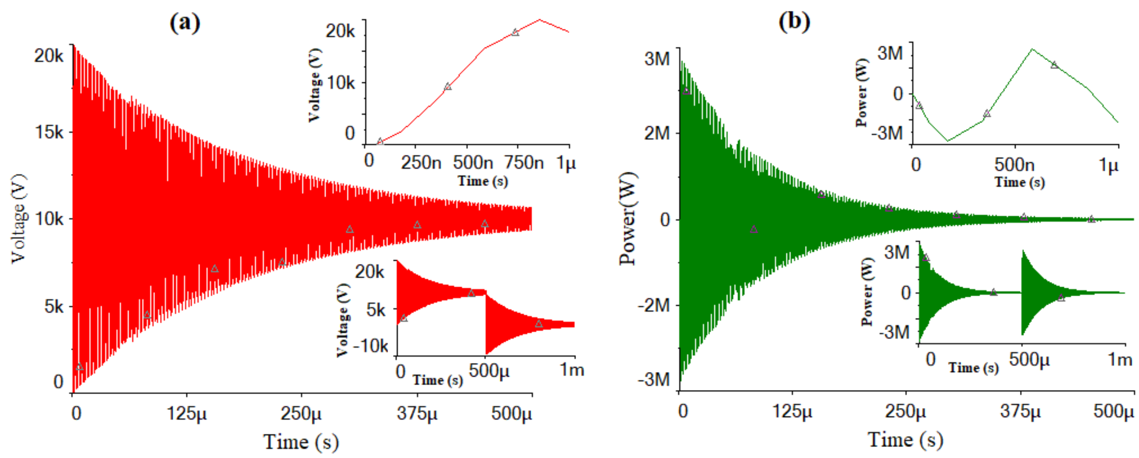

Fig. 7. (a) Voltage variations in the Blumlein transmission line for 500µs (for 1ms, 1µs: inset), (b) Power variations in the Blumlein transmission line for 500µs (for 1ms, 1µs: inset).

4. CONCLUSION

The simulation and analytical modelling of the spark gap, Blumlein circuit, and Blumlein transmission lines have been carried out to fabricate the prototype transversely electrical excited at atmospheric pressure (TEA) N_2 laser. We have analyzed and compared the voltage and power variation across the various components of the Blumlein circuit and spark gap for a single cycle and a more extended period at high input voltage. The behaviour of simulated voltage and power variations agreed well with the analytical modelling. This study could pave the way to fabricate the TEA N_2 laser, which generates UV coherent pulses for spectroscopy applications.

REFERENCES

[1] UK Patent 589127, **“Improvements in or relating to apparatus for generating electrical impulses**”, *Alan Dower Blumlein, filed October 10*, 1941, granted June 12, 1947.

[2] Fitzsimmons, W., et al. **"Experimental and theoretical investigation of the nitrogen laser."** *IEEE journal of quantum electronics* 12.10, pp. 624-633, 1976.

[3] Ashrafi, A., & Golnabi, H., **“Theoretical studies of electrical characteristics of the nitrogen laser”**. *International Journal of Engineering*, *7*(3), pp. 143-154, 1994.

[4] Hasson, V., H. M. Von Bergmann, and D. Preussler. **"Effective glow discharge excitation of nitrogen lasers at gas pressures ranging from 0 to 5 bar."** *Applied Physics Letters* 28.,1, pp. 17-18, 1976.

[5] Bergmann, Ernest E. **"UV TEA laser with 760-Torr N2."** *Applied Physics Letters* 28.2, pp. 84-85, 1976.

[6] Godard, Bruno. **"A simple high-power large-efficiency N 2 ultraviolet laser."** *IEEE Journal of Quantum Electronics* 10.2, pp. 147-153, 1974.

[7] Herden, W., **“Compact high-power sub-nanosecond nitrogen and “open-air”** *lasers at 760 Torr*. *Physics Letters A*, *54*(1), 96-98, 1975.

[8] Hussain, M., & Imran, T., **“Design and construction of prototype transversely excited atmospheric (TEA) nitrogen laser energized by a high voltage electrical discharge”.** *Journal of King Saud University-Science*, *27*(3), pp. 233-238, 2015.

[9] Schwab, A., and F. Hollinger. **"Compact high-power N 2 laser: Circuit theory and design."** *IEEE Journal of Quantum Electronics* 12.3, pp. 183-188, 1976.

[10] Stankov, K. A., S. Z. Kurtev, and I. Y. Milev**. "High-energy output from a short-channel N2 laser."** *Optics communications* 62.1, pp. 32-34, 1987.

[11] Zhao, Caifeng, and Jianqiang Wu. **"Modeling of Blumlein circuit and calculation of resistance and inductance of Laser Plasma."** *International Journal of Science, Technology and Society* 2.6, pp. 196-200, 2014.

[12] Hussain, M., Siddique, M. B., & Imran, T., **“Analysis of transversely electrical excited atmospheric (TEA) nitrogen laser and different**

parameters of the homemade ignition system". *Science International, 27(6*), pp. 5001-5004, 2015.

[13] Molina, Luis L., et al. **"Sub-nanosecond avalanche transistor drivers for low impedance pulsed power applications."** *PPPS-2001 Pulsed Power Plasma Science 2001. 28th IEEE International Conference on Plasma Science and 13th IEEE International Pulsed Power Conference. Digest of Papers (Cat. No. 01CH37251)*. Vol. 1. IEEE, 2001.

[14] Chen, Li, et al. **"He–SrCl2 vapour laser excited by Blumlein discharge circuit."** *Optics communications* 282.19, pp. 3953-3956, 2009.

[15] Waynant, Ronald W. **"A discharge-pumped ArCl superfluorescent laser at 175.0 nm."** *Applied Physics Letters* 30.5, pp. 234-235, 1977.

[16] Twati, Mohamed O., and A. Ben Otman. **"Distributed parameter analysis of a Blumlein-line N2 laser."** *Optics communications* 99.5-6, pp. 405-412, 1993.

[17] Hussain, Mukhtar, and Tayyab Imran. "**Simulation of Pulsed High Voltage DC Source and Blumlein Transmission Line."** *IOSR Journal of Applied Physics 9(1*), pp. 30-33

[18] Twati, Mohamed O., and Abubaker B. Otman. **"A Modified Approach for the Blumlein-line Laser Power Calculations: Electrical and Optical Power Waveforms."** *Journal of Wireless Communications* 2.1, pp. 1-6, 2017.

[19] Twati, Mohamed. **"A full distributed parameter model of a Blumlein-line laser circuit including the effect of time varying spark-gap inductance and resistance."** *2014 IEEE 27th Canadian Conference on Electrical and Computer Engineering (CCECE)*. IEEE, 2014.

[20] Habib, Bassam Hanna. **"A simple model of spark gap discharge phase."** *Engineering and Technology Journal* 31.9 Part (A) Engineering, pp. 1692-1704, 2013.