OPTIMIZATION OF POWER ABSORBED BY NITROGEN LASER IN COMPUTATIONAL

By

Mulugeta Setie

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN PHYSICS
AT
ADDIS ABABA UNIVERSITY
ADDIS ABABA, ETHIOPIA
JUNE 2012

ADDIS ABABA UNIVERSITY
DEPARTMENT OF
PHYSICS

Supervisor: Prof.A.V.Gholap

Examiners: Dr. Abebe Belay

Dr. Tadelech Atomssa

ADDIS ABABA UNIVERSITY

Date: **June 2012**

Author: **Mulugeta Setie**

Title: **Optimization of power absorbed by nitrogen laser in computational**

Department: **Physics**

Degree: **M.Sc.** Convocation: **June** Year: **2012**

Signature of Author

Table of Contents

List of Tables

List of Figures

Abstract

The optimization of power absorbed by nitrogen laser circuit were developed and scaling parameters are identified with MatLab algorithm so as to enable a study of the laser over its range of discharge modes. Results are presented for the critically damped laser gap and for the more typical case of damping factor 0.4. The analysis shows in a typical nitrogen laser the rate of rise of the laser gap voltage dV_g/dt prior to laser gap breakdown is 0.5kv/ns and such a (dV_g/dt) is required for a uniform breakdown across the laser gap for a good lasing action. The power absorbed by the channel is 70% when the laser gap circuit is critically danped. For the case of damping factor 0.4 the power absorbed is 65%. Thus it may be concluded that in the present work optimum power absorbed by the channel is 70%.

Acknowledgements

First and foremost, all praise and thanks to the Almighty God for his endless blessings, love and care bestowed upon me. Surely without his mercy, the completion of this work would have not been possible. As every project, this project is based on the work of many and with the support of many. At the university of Addis Ababa, I am also greatly indebted to my supervisor Prof. A.V. Gholap for his effort in providing the necessary support in the preparation of this work. I would like to thank Aksum University for its financial supports, my friend Endale and Mekuanint lemlem for their support and encouragement at many points on fortran programe. Finally i would like to thank All My family, they have been very supportive of my efforts. particularly my mother.

Chapter 1

INTRODUCTION

1.1 General Introduction

LASER is an abbreviation which mean that Light Amplification by Stimulated Emission of Radiation. This is a bit of a misnomer. A laser is actually an oscillator rather than a simple amplifier. The difference is that an oscillator has positive feedback in addition to the amplifier. "Light" is understood in a general sense of electromagnetic radiation with wavelength around 1 micron. Thus one can have infrared, visible or ultraviolet lasers.

One of the most important ultraviolet lasers is a nitrogen laser that has been the subject of several recent parametric studies aimed at determining the optimum operation conditions of the device. In these studies, the critical quantities for determining nitrogen laser performance are laser channel inductances and laser gap resistance r_g. Because these quantities determine the laser channel discharge current as well as the electrical power absorbed by the laser channel. The quantities, laser channel inductances and laser gap resistance r_g have been described in detail [1] as "unmeasurable" so that in many studies [1]-[4], they are either taken as parameters in the circuit analysis or computed using a gas discharge model, or deduced by matching theoretical and experimental voltage wave forms. While some of the studies have thrown light on these quantities $L_{g1}\&L_{g2}$ and r_g, a more direct method of measuring these quantities appears desirable. In this study, the laser channel discharge current in a Blumlein-type nitrogen laser is measured using electrical discharge by achieving an electrical pump in a given circuit in order to optimize the channel laser power absorption.

Based on the chemical stable molecular species, N_2, the nitrogen laser emits short pulses at high repetition rates. The repetition rate exceeding 100Hz can be obtained if we have a good design of electrodes, high voltage source and spark gap switch.

Pumping is achieved using an electrical discharge, excited transversely in a laser channel through which N_2 gas flows at a pressure of about 40 Torr(in the case of low pressure nitrogen laser) to one atm and above[in the case of TEA nitrogen laser]. The excitation rate by the direct electron impact for the transition $X \to C$ is much larger than that of $X \to B$. However, the life time of state C is only about a maximum of 40ns(at a pressure of 40 Torr), Where as the the corresponding state value of B is about $10\mu s$ it is obvious that the lower level of lasing transition has a longer life time than that of the upper, then the lasing action may not be possible at all, or might be possible only in a pulsed mode. This suggests that exchange processes are involved in the excitation scheme of this system. In order to have good lasing system and high output of nitrogen laser, there should be well structured design system and optimized power absorption by N_2 laser

1.2 Literature Review Of Nitrogen Laser

The nitrogen laser was developed in 1963 by H. G. Heard, who succeeded in producing 10-W pulses of UV light (which sounds impressive enough but with pulse widths in the nanosecond range, the average power of such a laser was incredibly low). Development continued and TEA (transverse electrical discharge at atmospheric pressure) nitrogen lasers capable of producing megawatt powers are available. This laser was an important milestone in UV laser development that led directly to the more powerful excimer laser. Among other things, development of the nitrogen laser led to advances in the production of high-speed, high current discharges required for a high-efficiency nitrogen laser and later for the excimer laser. Today, the nitrogen laser is found primarily in the lab and is still a useful source of coherent UV light, producing pulses with Milli-joule energies and pulse widths around 10 to 20 ns. Owing to the ease of construction, it is also a favorite home-built laser for both amateur laser constructors and small labs on a budget. These inexpensive lasers are commonly used as workhorses in biology and chemistry labs [5]. For this rapid and extensive development, there were various modifications on the original work, reported by Leonard[6], Gerry[7], Shipman[8] and other researchers. Most of the information available from the field of nitrogen laser publications more less deal constructive details and also describe the dependence of the laser out put on different parameters , such as the gas pressure in the laser tube,the spark gap inductance, the characteristics impedance of transmission line, the charging voltage and the nature of driving electrical circuit. Efficient operation of pulsed gas laser having very short upper state life times depend strongly on the property of the discharge circuit.Many papers have been published on the optimization of the energy transfer from the source to the laser channel.

The realization of lasing action in N_2 second positive system was reported by H.G Heard in 1963 [9]. Heard has seen that the second positive system of N_2 (i.e $C^3\pi_u \rightarrow B^3\pi_u$) at 337.1nm to be in the stimulated emission,and the theory of pulsed nitrogen laser system has been considered by Ali et.al[10]. A general rate equation analysis for three level laser UV laser system has been only done by Elton et.al [11]. The transition $C^3\pi_u \rightarrow B^3\pi_u$ of N_2 is an example established by the lower state of the transition electron collision. Super radiant oscillation has been observed, in this transition at power level in excess of 2MW for a pulse length of 10ns. The calculation indicates that the preferential excitation of the nitrogen $C^3\pi_u$ state is $\sim \Pi\alpha_o$ is near 15eV. Since the lower state of the transition is metastable state on the time scale of interest, a rapid rising high E/p discharge is required, in addition to direct excitation by collision, refined theoretical treatment of the nitrogen second positive system have included the effect of collisional ionization of the state $C^3\pi_u$ [7]. Finally we observe that N_2 second positive lasers is increasing at times it is unfavorable , one way to over come this problem, and probably the best means is to develop home built lasers using locally available materials. It is hoped that researchers effort in this area will increased in the future. Laser vary in complexity from simple home built nitrogen laser which delivers only a pulsed 20kwatts of UV light at 337.1nm in a few nanosecond flashes to, elaborate every high power multi beam line system.

In addition to its relative simplicity of construction, the nitrogen laser is one of the most useful becuase of its effectiveness as a pump for tunable dye laser and this combination is particularly powerful since it open ups the possibility relative and extensive laser based spectroscopy.

1.3 Justification

The out puts of nitrogen laser are the results of different physical setting and internal parametric values in its design. Such as Laser channel, laser gap, spark gap, capacitors setting & their parametric values. Because the laser channel discharge current in a Blumlein-type nitrogen laser is measured using electrical discharge by achieving an electrical pump in a given circuit in order to optimize the channel laser power absorption and the laser gap voltage which is explained as below.

The transversally excited pulses of nitrogen laser depend for its operation on two important requirements:

1) A uniform discharge occurring throughout the length of the discharge channel. This uniformity depends on a sufficiently high rate of voltage dV/dt across the laser gap

2) A sufficiently optimum (hight) power absorption (rate of energy absorption) in the laser gap plasma during the main discharge. These requirement may be seen in the following way.

The laser channel consists of two long parallel electrodes forming a constant gap of about 1cm along the whole length $\sim$ 50cm. A constant flow of N_2 gas maintained at desirable pressure. Although the gap may be set at a uniform spacing, local irregularities exist and at any given times the breakdown voltage across will vary if only by a small amount from point to points along the gap. If such a gap is subjected to rising voltage difference across it, i.e. dV/dt is smaller than when the voltage difference becomes sufficient to breakdown at that point of the gap will break down at that point breakdowns, a pulse of zero voltage will traverse the length of the gap at the speed of electromagnetic wave, thus, stopping any further breakdown except at the first point of breakdown.

However, an infinitively fast rising pulse is applied i.e dV/dt then after the first point breakdown and as the pulse of zero voltage traverse away from the point of break down the other points in the channel also break down because before the pulse of zero voltage arrives, these point have already been stressed to breakdown by the infinitively rising voltage pulse, it may be seen from this argument that for uniform break down the rate of rise of gap voltage dV/dt must be such that the point (in the gap) with the highest breakdown voltage(due to surface difference) rise to this breakdown voltage before the pulse of the zero voltage arrives from the first break down point. Thus, there is in general a minimum dV/dt for uniform breakdown. This value will of course depend on uniformity of gap spacing and electrode surface conditioning. In general again, however, nitrogen laser gaps will have been built to a high standard of uniformity of gap setting and gap surface conditioning. It then remains to determine a minimum dV/dt required for good uniformity. To help answer this question a lumped parameter model for the nitrogen laser circuit is given. In the present work the circuit equations are written with greater details and are non-dimensional so that the scaling parameters can be identified. The scaling parameters are then varied to cover a wide range of operation of the nitrogen laser. The computations are used to determine the rate of rise of laser gap voltage dV/dt and the rate of energy absorption (optimization of power absorption) at laser gap as function of the scaling parameters.

1.4 Objectives Of The Project

The objective of this project is to

- studying parameters of nitrogen laser
- establishing the value of nitrogen laser rate of rise voltage for the uniformity of discharge through the laser channel and
- optimizing the power absorbed by nitrogen laser

1.5 Project Structure

Chapter one is an introduction to the Nitrogen laser. Chapter two presents the theory of the Nitrogen laser. Chapter Three deals with a parametric model which employs an analysis of the laser circuit before and after uniform discharge. Chapter four shows the results and their discussion. Chapter Five is the conclusion and future work

Chapter 2

Energy Level Diagram Of Nitrogen Laser

The UV nitrogen laser is based on a three level pumping scheme.The ground state $X^1\sum_g^+$ (level 1) and two electronically excited levels $C^3\Pi_u$ (level 3) and $B^3\Pi_u$ (level 2) are shown in figure below.

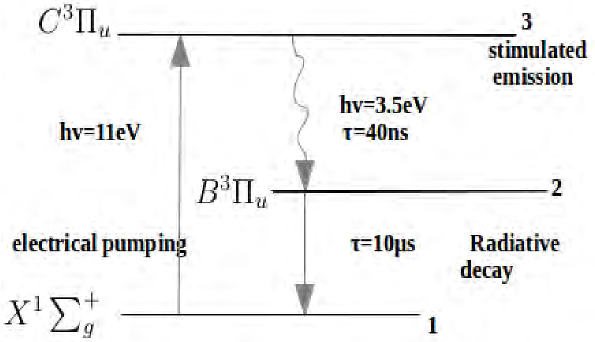


Figure 2.1: Three levels pumping scheme of Nitrogen laser

During an electrical discharge, the nitrogen molecules are excited from the ground level to the upper level 3. The energy difference between level 1 and level 3 is of the order 11 eV. The transition from level 3 to level 2 corresponds to 3.5 eV giving rise to the 337.1 nm laser radiation. The upper laser level depopulates either radiationlessly via collision with electrons and other nitrogen molecules or through stimulated emission in to the lower level 2 with a life time of 40ns. Level 2 on the other hand, is a metastable state with life time of about $10\mu s$

2.1 Population Inversion Of Nitrogen Laser

One of the prerequisites for lasing to take place for continuously, or to give an even-pulsed output, is population inversion. It takes place when there are more atoms in the upper level than the lower level. Atoms are excited to the upper level through a process called pumping, which differs for different lasing media. Thus, pumping mechanism principle be able to excite atoms or molecules continuously to achieve a uniform output of the laser pulses. For nitrogen laser no vacuum pump is required as laser operates at atmospheric pressures,however, the electrical discharge circuitry must be extremely fast the laser to work.

2.2 Pumping Mechanism For Nitrogen Laser

A nitrogen molecule like any other diatomic molecule, possesses vibrionic energy levels that constitute both vibrational and electronic states. These energy states are mainly separated by the change in electron energy of the atoms, and a small contribution resulting from the vibrations with in the nitrogen molecule themselves. The laser action therefore involves a series of the transitions, resulting from the changes in vibrational and electronic states of the nitrogen molecules, which are nearly spaced to flavor the emission of ultraviolet radiation at 337.1 nm [12]. The pumping mechanism in a nitrogen laser,involves collision of high energy electrons with the gas molecules in a laser tube through electron impact excitation. The accelerated electrons in the laser tube strike the nitrogen molecules, thus exciting them to a higher electronic energy state. Figure 2.1 shows the energy level scheme for a nitrogen laser, with each level showing a series of vibrational energy level, which depends on the internuclear separation of the molecule. The laser normally starts when the nitrogen molecules become excited by an electric discharge in the lasing tube from the electronic ground state, la-belled $X^1\sum_g^+$ energy band to the upper lasing level, label led $C^3\Pi_u$ energy band. The molecules at the upper lasing level are unstable, thus they decay to the lower lasing level, label led as $B^3\Pi_u$ energy band, by emitting photons of ultraviolet radiation at 337.1 nm. When a molecule emits a photon as it falls to the lower lasing level, it then decays to a metastable state where it stays. Thus a nitrogen laser is effectively a three-level laser. The transition lifetime of the gas molecules from the upper lasing level to the lower lasing level is very short (40 ns) as compared to lifetime for the transition between the lower lasing level and the metastable state (about 10 μs) [13]. Thus the population of the gas molecules at the lower level exceeds that at the upper lasing level. This means that the lasing process will terminate, since the condition for lasing to take place is violated. Creating a population inversion at the upper lasing level in this case, is only possible if the pump power from the source is sufficient to have the nitrogen molecules in the upper lasing level as quickly as possible. Gas lasers in general, are pumped directly by electron impact excitation. The gas molecules are excited from the ground level to the upper level through collisions with the electrons accelerated by the electric field set-up between the electrodes of the discharge chamber.

On the other hand, When atoms get excited (gain energy) their electrons move up energy levels. Population inversion occurs when over half of the population of atoms is in the same excited state. When these electrons decay back down to their ground state a photon is emitted that has an energy $E = h \times f$ equal to the the difference between the energy levels of the drop. If the photon passes an atom in the excited state, and this photon has an energy equal to an energy drop that an electron in the excited atom can make, then the photon stimulates the electron to drop to the lower energy level. At this situation, a photon with the same frequency and phase with the photon that passed atom, is emitted. This process is called stimulated emission.When stimulated emission occurs in the presence of a population inversion, the photons emitted will have the same frequency and in the same phase. This emitted light is laser light.

The energy level of the nitrogen molecule as they apply to this laser are outlined in fig. 2.1. Each level shown is actually a series of vibrational levels dependent on the inter molecular separation. The laser begins when a nitrogen molecule is excited by the direct collision with electrons in the discharge to enter the ULL(Upper Lasing Level). From the ULL the molecule falls to the LLL(Lower Lasing Level) by emitting a photon of UV(Ultraviolat) light in the process. Transitions in the normal nitrogen laser is at 337.1nm. After emitting a photon in the transition, the molecule then falls to a metastable state and finally to the ground state. Although not a four level laser in the proper sense(the system lacks a pump level because the ULL is pumped by direct electron collisiom), it is cetrainly not a 3-level system since it does feature of a distinct LLL. In this respect the system resembles that of a copper -vapor laser with inclusion of a metastable

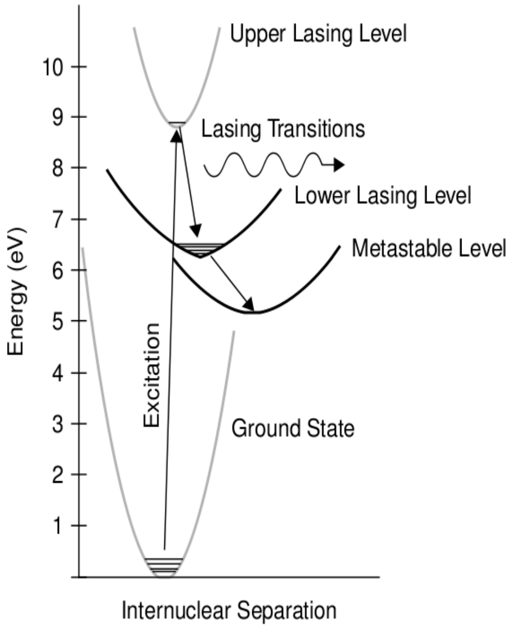


Figure 2.2: Molecular nitrogen laser energy levels

state. The gain medium is nitrogen molecule in the gas phase.A nitrogen laser is a 3-level laser, therefore, the upper lasing level of nitrogen laser is directly pumped, imposing no speed limits on the pump. This is normally provided by direct electron impact; the electrons must have sufficient energy to excite the upper laser level. Typically reported optimum values are in the range of 80 to 100eV per Torr cm presure of nitrogen gas.

2.3 Nitrogen Laser Structure

The basic requirement for a practical nitrogen laser is to supply a massive electrical current (i.e. a huge quantity of electrons) with a fast rise time and short pulse length to excite the gas. To achieve this, most nitrogen lasers use an electrical configuration called a Blumlein configuration, which generates a massive over voltage across the laser channel (and subsequent large current through the lasing gas) with a rise time of nano- seconds. A Blumlein configuration is shown schematically in Figure 2.2 where we find two capacitors essentially in parallel separated by the laser channel itself. Both capacitors charge simultaneously through the charging inductor (which offers little electrical resistance to the charging current) until the spark gap fires when the break down voltage is reached (typically, about 15 kV for a small laser). In simplest form, a nitrogen laser may operate as a relaxation oscillator, repeatedly charging and firing; the use of triggered spark gaps or thyratrons allows the laser to be triggered as required. The gap now conducts essentially short-circuiting C_1 and draining charge from it, making the top terminal of C_1 negative. A massive voltage difference appears quite suddenly across the laser gap since the left side of the tube is now negative and the right side still positive. Charge from C_2 flows across the laser channel as a pulse of very high electrical current, in many cases thousands of amperes. The electrical dynamics of the laser are not as simple as a discharge, though, since the laser tube has long transverse electrodes over which the high current must be distributed. With a short discharge time necessitated by the short upper- lasing-level lifetime, the laser is best excited by a traveling electrical wave which starts at the rear of the laser and moves forward at the speed of light exciting nitrogen molecules as it progresses. To accomplish this, capacitors are fabricated as long, dis tributed capacitances parallel to the laser tube.

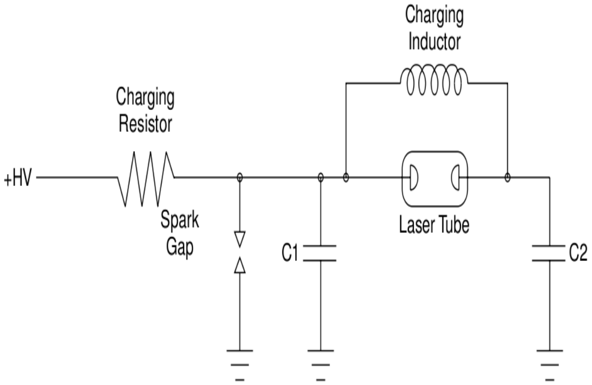


Figure 2.3: Electrical schematic of a Blumlein laser

The initiating spark gap is placed at the rear of one capacitor so that the electrical pulse begins at the rear of the laser first and travels toward the front of the laser. In many cases it is possible to design the laser as a transmission line for efficient transfer of electrical energy into the lasing volume. The sequence of events during firing of the laser is outlined in Figure 2.3. In this particular design, common for small laboratory-type nitrogen lasers, the capacitors are fabricated on an epoxy-glass substrate. Two capacitors are formed with copper foil on the top of the board (there is a separation between the two capacitors underneath the laser tube, so they are not visible in the figure), and the bottom of the board is the common terminal for both. The spark gap that initiates electrical discharge is mounted on the left capacitor near the rear of the laser. In the simplified figure (in which details such as the charging inductor are omitted for clarity) both capacitors are charged to a high voltage equally, so no voltage difference appears across the laser channel. As the capacitors are charged, the voltage across the capacitors as well as the spark gap rises until breakdown occurs (in Figure 2.3b) and the spark gap conducts. Charge can be visualized in the figure as moving toward the spark gap in an arc centered around the spark gap. No voltage appears across the laser channel until the charge at the rear of the left capacitor for the laser has been drained and a voltage differential appears at the rear of the laser channel. The discharge in the laser thus begins here. As the traveling wave in the capacitor spreads, the voltage differential travels toward the front of the laser channel at the speed of light, generating a discharge that also travels toward the front of the laser. Light emission follows the discharge and a beam emerges from the laser.

A practical nitrogen laser based on this design is shown in Figure 2.4. The initiating spark gap is visible in the upper-left corner. It emits an intense flash of light since high currents pass through it. Other visible features include the charging inductor, which bridges the laser channel and the charging resistor near the spark gap. This is a flowing-gas laser in which nitrogen gas under low pressure flows slowly through the tube. A needle valve used to regulate flow is also seen in the lower left of this laser. After initiation of laser action by the spark gap and discharge through the laser channel, the laser pulse is

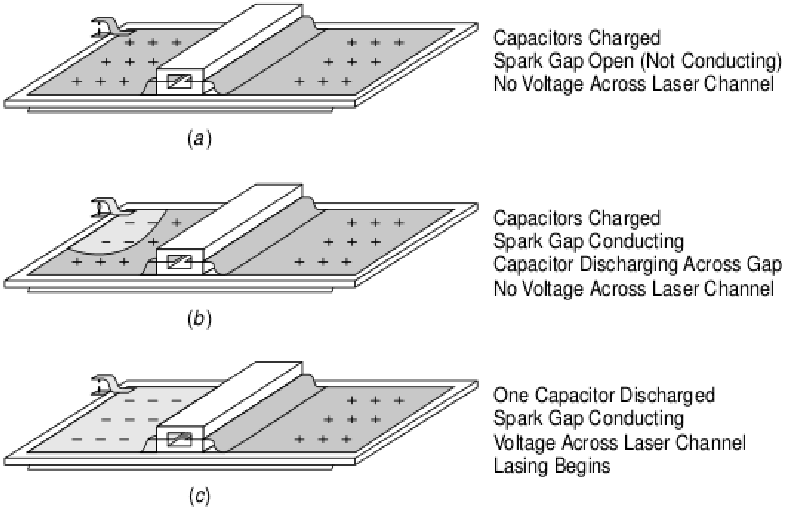


Figure 2.4: Nitrogen laser discharge sequence

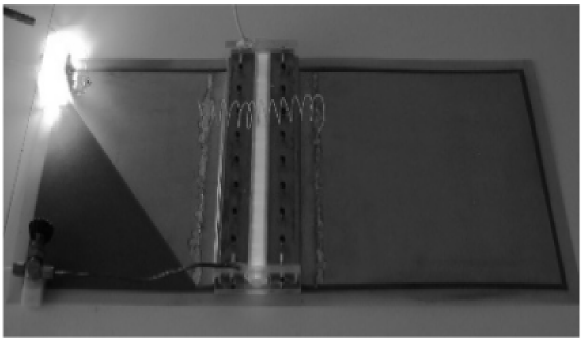


Figure 2.5: Practical nitrogen laser

generated and will continue until population inversion ceases. Laser action ceases regardless of how long the electrical pulse lasts, so it is pointless to design a laser with a longer discharge time than this. This parameter determines the size of the capacitors employed in the laser. As well as operating at low pressures (generally, 20 to 60 torr), nitrogen lasers may operate at atmospheric pressure in a TEA configuration. These lasers are physically similar to the low-pressure types described in this chapter, and most use a Blumlein configuration. In the case of a TEA nitrogen laser, though, the lifetime of the ULL decreases to about 2.5 ns. The requirements for a fast discharge are even more pronounced in a TEA laser, which must be constructed to keep induc tances in the discharge path to an absolute minimum. With this in mind, dielectrics for capacitors are kept very thin (since the intrinsic inductance of a transmission-line capacitor is proportional to the thickness of the dielectric) and the laser channel is mounted directly on top of the capacitors.

A practical TEA laser is pictured in Figure 2.5, in which the spark gap is located in the upper-right corner of the photo and the long transverse electrodes are visible down the center of the laser. The laser pictured operates using open air as the lasing gas. This is possible since air is 78% nitrogen, although output power decreased by 80% over the use of pure nitrogen gas. A possible source of inefficiency is evident in that the discharge reveals hot spots or arcs. Unlike the low-pressure laser, which features a consistent and even discharge between the electrodes, discharges in TEA lasers tend to concentrate and resemble individual sparks. For efficiency, measures must be taken to even out the discharge, including dilution of the nitrogen gas with helium, use of an electrode structure consisting of multiple points, and preionization of the discharge channel with a high-voltage corona or ultraviolet radiation before the main laser discharge ensues.

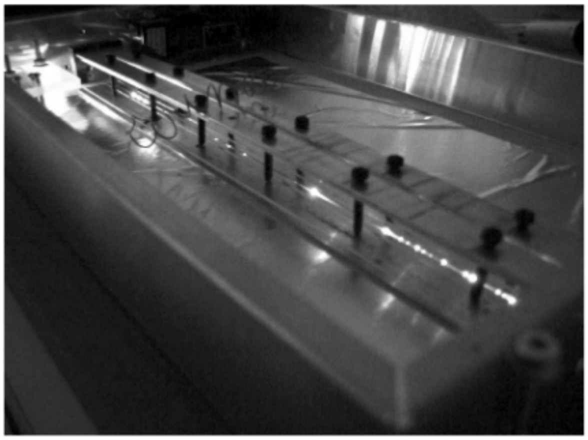


Figure 2.6: TEA Nitrogen laser

Most small commercially available nitrogen lasers use spark gaps for their simplicity. These spark gaps are filled with nitrogen gas for reliable, predictable firing. In the case of a TEA laser, the gap may be placed inside the same pressure vessel as the rest of the laser. Filling with nitrogen also eliminates the objectionable production of ozone when the gap fires. In some larger lasers, thyratrons are used instead of spark gaps. Thyratrons are switching devices that use mercury vapor or hydrogen gas and feature incredibly fast rise times, many times faster than spark gaps. As well as faster switching times, thyratrons also allow triggering on command instead of simply triggering when the spark gap is overvoltaged, an important feature when this laser is used in a laboratory experiment requiring synchronization and precise timing. Because of the low inductance discharge path required, essential elements of the nitrogen laser, such as storage capacitors and switches (thyratrons or spark gaps), are an integral part of the laser itself. To charge the capacitors, a basic high voltage supply is required, the supply current of this supply limiting the maximum firing rate for the laser. Designs for high-voltage power supplies vary from simple neon-sign transformers to efficient and compact switching power supplies. These supplies are usually housed in the main laser housing for safety. In many low-pressure nitrogen lasers, gas flows continually through the lasing channel. This helps to eliminate impurities generated during the discharge as well as cool the laser. Gas flow is quite slow, so consumption is minimal. Many small commercial nitrogen lasers are of the TEA variety and use a sealed laser channel, so a gas supply and vacuum pump are not required, making a much simpler laser for laboratory use. With a fast enough discharge time, some low-pressure nitrogen lasers can also operate using hydrogen gas (with a transition in the extreme UV at 160 nm) or neon gas (with a visible transition at 540.1 nm). Both of these alternatives have shorter upper-level lifetimes than nitrogen does, so an extremely fast laser discharge is required (much faster than normally required in a nitrogen laser).

2.4 Out put Characteristics Of Nitrogen Laser

Beam quality is poor in a nitrogen laser. Being a superradiant laser with enormous gain, the output really consists of highly amplified spontaneous emission. In a lower-gain laser, photons traverse the cavity many times, stimulating the emission of many more photons of exactly the same wavelength. In a nitrogen laser, photons often make only one pass through the amplifier before exiting. Collimation is hence poor and divergence is quite large compared to other types of lasers. Coherence length is also poor, since the spectral width of the laser output is quite wide. Molecu- lar nitrogen lases at 61 known wavelengths between 336.4903 and 337.9898 nm, an extraordinarily wide range for a laser, but the vast majority of lines are clustered around 337.1 nm, so the FWHM of the combined output from these lines is about 0.1 nm. Since gain is high, wavelength selectors are ineffective in allowing single- line operation.

Chapter 3

NITROGEN LASER PARAMETERS

Several parameters play an important role in the optimum operation of the nitrogen laser. A uniform discharge throughout the length of the laser discharge channel and a sufficiently high rate of energy absorption in the laser gap plasma during the main discharge are required for good operation. The uniformity depends on how fast the laser gap voltage rises as well as on laser surface conditions and gap setting while the energy absorption is characteristic of the nitrogen gas and achieved through the use of the flat plate capacitors. Experimentally, it is very stringent to achieve the required rise rate of laser voltage sufficient to cause the laser to breakdown uniformly. In order to achieve suitable design parameters that meet the minimum rate of rise of laser gap voltage, a parametric model which employs an analysis of the laser circuit before and after uniform discharge has been developed for the nitrogen laser

The main operation of a nitrogen laser can be explained by refering to the Blumlein transmission line and the laser channel. When the laser channel breakdown there is a plasma which is mainly inductive with a very small resistance.

A typcal nitrogen laser circuit may be represented by fig.3.1. The fast parallel plate capacitors C_1 and C_2 with very low inductances L_1 and L_2 are charged by a constant voltage V_0 and connected to the laser gap represented by a resistance r_g and inductance L_{g0} as shown in the diagram. The inductances L_{g1} and L_{g2} represent the channel inductance on either side of the laser gap.The capacitor C_2 is connected to an external spark gap represented by resistance r_e in the diagram and with inductance L_e. Typcally $C_1 \sim 100nF$, $C_2 \sim 50nF$, $L_1 \sim 0.40nH$, $L_2 \sim 0.18nH$, $L_{g1} = L_{g2} \sim 0.8nH$, $L_{g0} \sim 0.3nH$, and $L_e \sim 30nH$. The external spark gap resistance r_e has a value such that the external circuit i.e $L_2 - L_e - r_e - C_2$ is fairly oscillatory; whilst for good and fast energy transfer one wuold hope to design for r_g to have such a value that the laser discharge circuit i.e $C_1 - L_1 - L_{g1} - r_g - L_{g0} - L_{g2} - L_2 - C_2$ should be nearlly critically damped. However, one would expect that typically this laser circuit would be less than critically damped.

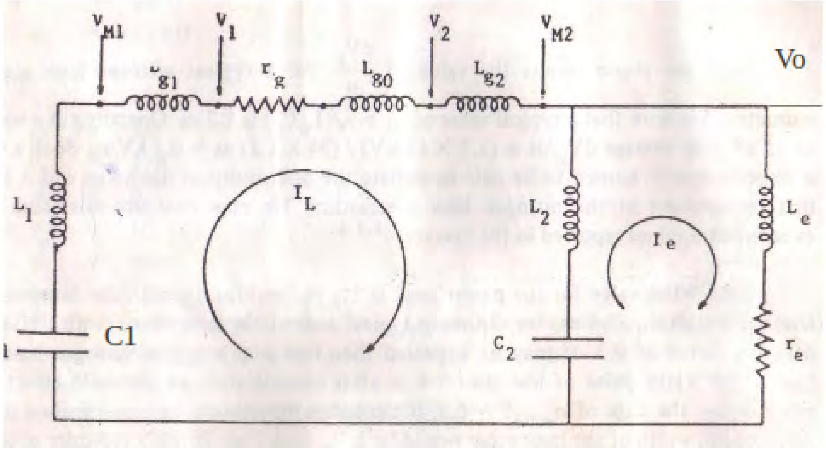


Figure 3.1: Equivalent circuit of a nitrogen laser

When the external spark gap switches at t = 0 the voltage V_2 drops from its initial value V_0, swings negative towards -V_0 with a time constant given by $\sim \sqrt{L_e C_2}$ since $L_e >> L_2$, thus providing the rate of rise of gap voltage of the order of $\frac{2V_0}{\sqrt{(L_e C_2)}}$ which should cause the laser gap to not only breakdown, but to breakdown uniformaly at time $t = t_s$. The main discharge should then occur with a short time constant $\sim \sqrt{(L_1 + L_2 + L_g)(C_1 C_2)/(C_1 + C_2)}$, where $L_g = L_{g1} + L_{g2} + L_{g0}$, modulated with a slower discharge with a small time constant $\sim \sqrt{L_e(C_1 + C_2)}$ which subsequently removes all the stored energy through the external spark gap r_e.

The equations which describe the perfomance of dischsrge circuit are given below: For $0 \leq t < t_s$ (before the laser gap breakdown)

$$I_2 = 0 \tag{3.0.1}$$

$$L_2\frac{dI_e}{dt} + L_e\frac{dI_e}{dt} + r_eI_e = V_0 - \frac{\int I_edt}{C_2} \tag{3.0.2}$$

where I_2 is the laser current which equals to I_L. I_e, L_e, and r_e are the laser spark gap current, inductance and resistance, respectively. C_2 and L_1 are the capacitance and inductance of the second flat plate capacitor. V_o represents the initial voltage of the capacitor and t_S is the time at which the laser gap breakdown. Initial conditions are obtained for Eq.(3.0.2) by setting $I_e = 0$ at t = 0.

$t = 0$, $I_e = 0$, $\frac{\int I_edt}{C_2} = 0$, $\frac{dI_e}{dt} = \frac{V_0}{L_e+L_2}$ After the laser gap breakdown, i.e at $t > t_s$, Eq (3.0.1) and (3.0.2) are replaced by the following equations:

$$L_2\frac{dI_e}{dt} - L_2\frac{dI_2}{dt} + L_e\frac{dI_e}{dt} + r_eI_e = V_0 - \frac{\int I_edt}{C_2} + \frac{\int I_2dt}{C_2} \tag{3.0.3}$$

and

$$\begin{aligned} L_1\frac{dI_2}{dt} + (L_{g1} + L_{g0} + L_{g2})\frac{dI_2}{dt} + L_2\frac{dI_2}{dt} - L_2\frac{dI_e}{dt} + r_gI_2 = \\ V_0 - \frac{\int I_2dt}{C_1} - V_0 - \frac{\int I_2dt}{C_2} + \frac{\int I_edt}{C_2} \end{aligned} \tag{3.0.4}$$

At the moment of laser gap breakdown i.e $t = t_s$, the values of I_e, $\frac{dI_e}{dt}$, and $\int I_edt$ are known from the numerical integration of equation (3.0.2) whilst the other values necessary to start the integration of equations (3.0.3) and (3.0.4) are

$t = t_s, I_2 = 0, \int I_2dt = 0$ and

$$\{\frac{dI_2}{dt}\}_{t_s} = \frac{\{\frac{\int I_edt}{C_2}\}_{t_s} + \{\frac{L_2dI_e}{dt}\}_{t_s}}{(L_1 + L_2 + L_g)}$$

where L_g and r_g are the laser inductance and gap resistance respectively; L_1 and C_1 are, respectively, the inductance and capacitance of the first capacitor. At t = t_s the initial values of I_e, $\frac{dI_e}{dt}$ and $\int Iedt$ are obtained from numerical integration of Eq.(3.0.2) whilst the other values necessary for the integration in Eqs.(3.0.3) and (3.0.4) are obtained by additionally setting $I_2 = 0$. Eqs.(3.0.5) through (3.0.4) are then non-dimensionalised so that scaling parameters are identified. These scaling parameters are varied to cover a wide range of operation of the nitrogen laser. The computations are used to determine the rate of rise of laser gap volt age dVg/dt and the rate of energy absorption at the laser gap as a function of the scaling parameters.

The following relationships are used in the normalization process:

$\tau = \frac{t}{t_0}$,$i_e = \frac{I_e}{I_0}$, $i_2 = \frac{I_2}{I_0}$, where $t_0 = \sqrt{(L_2C_2)}$ and $I_0 = \frac{V_0}{\sqrt{(\frac{L_2}{C_2})}}$,

This normalisation procedure gives us the governing equations and conditions in the following form: $0 \leq \tau < \tau_s$,

$$\frac{di_e}{d\tau} = (1 - \int i_e d\tau - \alpha_e i_e)/(1 + \beta_e) \tag{3.0.5}$$

with starting conditions: $\tau = 0$ $i_e = 0$, $\int i_e d\tau = 0$, and $\frac{di_e}{d\tau} = \frac{1}{1+\beta_e}$ Where the scaling parameters $\beta_e = \frac{L_e}{L_2}$, and $\alpha_e = \frac{r_e}{\sqrt{\frac{L_2}{C_2}}}$

For $\tau \geq \tau_s$

$$\frac{di_e}{d\tau} = \frac{(1 - \int i_e d\tau + \int i_2 d\tau - \alpha_e i_e + \frac{di_2}{d\tau})}{1 + \beta_e} \tag{3.0.6}$$

and also we have

$$\frac{di_2}{d\tau} = \frac{(\int i_e d\tau - (1 + \delta) \int i_2 d\tau - \alpha_e \alpha_1 i_2 + \frac{di_e}{d\tau})}{1 + \beta_e + \beta_g} \tag{3.0.7}$$

With the starting conditions for this phase given by:

$\tau = \tau_s$, $i_e = (i_e)_{\tau_s}$, $\int i_e d\tau = (\int i_e d\tau)_{\tau_s}$, $\frac{di_e}{d\tau} = (\frac{di_e}{d\tau})_{\tau_s}$, being by the numerical integration of equation (3.0.5) upto $\tau = \tau_s$ and also at $\tau = \tau_s$, we have

Where the scaling parameters are:

$\beta_1 = \frac{L_1}{L_2}$, $\delta = \frac{C_2}{C_1}$, $\alpha_1 = \frac{r_g}{r_e}$, and $\beta_g = \frac{L_g}{L_2}$

Besides the values of i_e and i_2 other important quantities to be obtained from these exercise are:

a) Laser gap voltage: For $\tau \leq \tau_s$;

$$\nu_g = \frac{di_e}{d\tau} + \int i_e d\tau \tag{3.0.8}$$

and for $\tau \geq \tau_s$

$$\nu_g = \frac{di_e}{d\tau} + \int i_e d\tau - \int i_2 d\tau (1+\delta) + (1+\beta_1+2\gamma\beta_g)\frac{di_2}{d\tau} \tag{3.0.9}$$

where $\gamma = \frac{L_{g1}}{L_g} = \frac{L_{g2}}{L_g}$, or it is the ratio of channel inductance on either side of the gap to the laser inductance

It is the worthwhile to note that the measured voltage across the channel is taken between the points V_{M1} and V_{M2}, in figure 3.1, and is given by

$V_M = V_{M1} - V_{M2}$

$$= \int i_e d\tau - \int i_2 d\tau + \frac{di_e}{d\tau} - \frac{di_2}{d\tau} - \delta \int i_2 d\tau - \beta_1 \frac{di_2}{d\tau} \tag{3.0.10}$$

It should be noted that before laser gap switching this voltage is equal to ν_g the spark gap voltage

b) power absorbed by laser gap

The power absorbed by the laser gap $I_2^2 r_g$ may be normalised to the average power of discharge of the $C_1 - L_1 - L_g - L_2 - C_2$ circuit. This average discharge power be written as

$P_g = \frac{\frac{1}{2}C_1 V_0^2}{\sqrt{(L_1+L_2+L_g)(\frac{C_1C_2}{C_1+C_2})}}$. Or $I_2^2 r_g$, the power absorbed by the laser gap can be computed and its optimum graph is shown in figure 4.1 and 4.2.

C) Effective parameters controlling discharge modes

The performance of the laser depends on the discharge modes of

(a) the $C_2 - L_1 - L_e - r_e$, circuit (external circuit) and

(b) the $C_1 - L_1 - L_g - r_g - L_2 - C_2$ circuit (the laser gap circuit).

The mode mention here refers to the degree of damping in the respective circuit ideally from the electrical parameters one would like to have the external circuit of current to be nearly undamped in order to have the biggest voltage reversal thus enhancing the maximum value of V_g. On the other hand for the laser gap circuit of the biggest power developed in the gap is for the case of critical damping.

The effective parameters controlling the damping of these two circuits are:

1. For the external circuit

$$\alpha_{effe} - _e = \alpha_e \sqrt{\frac{L_2}{L_2 + L_e}} = \alpha_e \sqrt{\frac{1}{1 + \beta_e}} \tag{3.0.11}$$

2. For laser gap circuit

$$\alpha_{effe} - _L = \frac{\frac{r_L}{L_1 + L_2 + L_g}}{\frac{C_1 C_2}{C_1 + C_2}} = \alpha_e \alpha_1 \sqrt{\frac{1}{(1 + \beta_1 + \beta_g)(1 + \delta)}} \tag{3.0.12}$$

3.1 Integration Procedure

The computation of this model is performed by numerical integration using Euler Linear-approximation method to solve the more complex integral-differential equations of the system and Matlab algorithm for the graphic results in the system. To begin the integration, I need to know the conditions at the start i.e $\tau = 0$. For this model, take the initial conditions as $\tau = 0$, $i_e = 0$, $\int i_e d\tau = 0$, and $\frac{di_e}{d\tau} = \frac{1}{1+\beta_e}$ for Eq.(3.0.5). Starting with known values of $\frac{di_e}{d\tau}$ and $\int i_e d\tau$ at $\tau = 0$, the values of $\frac{di_e}{d\tau}$, $\int i_e d\tau$ and i_e at $\tau = (\tau) + \Delta\tau$ are computed by using a linear approximation method.Thus,

$$\int i_e d\tau = (\int i_e d\tau)_{perviousvalues} + (i_e)_{perviousvalues} \Delta\tau + 0.5 * (\frac{di_e}{d\tau})(\Delta\tau)^2 \tag{3.1.1}$$

$$i_e = (i_e)_{perviousvalues} + \frac{di_e}{d\tau}(\Delta\tau) \tag{3.1.2}$$

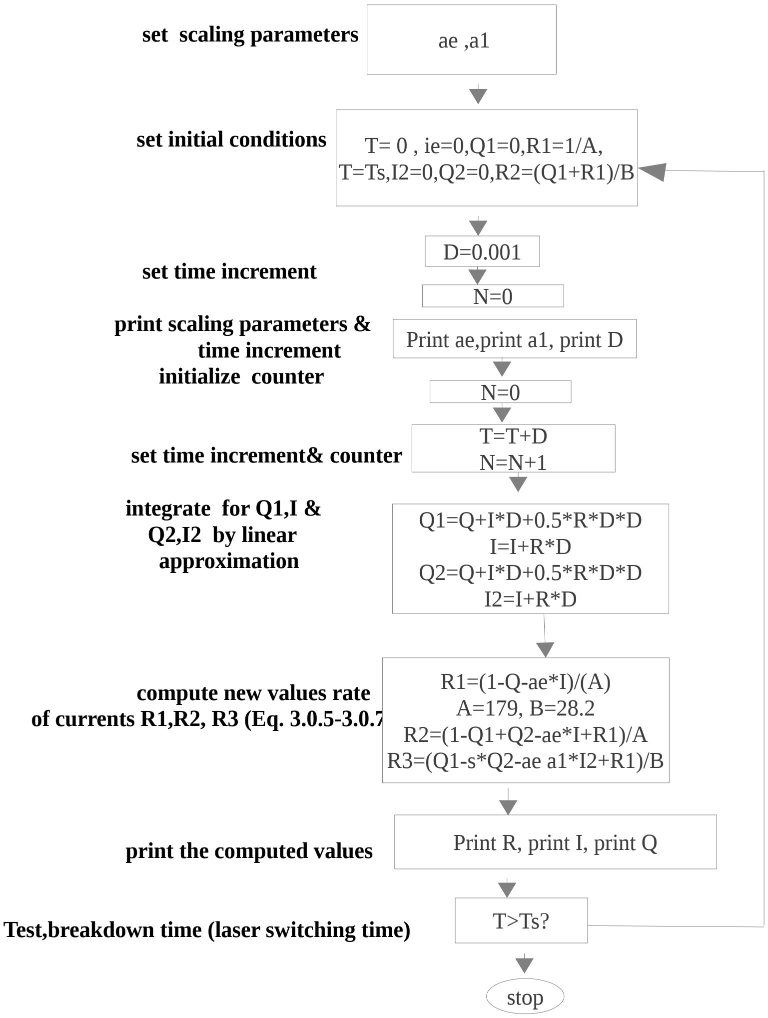
Similarly, the integration for other Equations (3.0.6) and (3.0.7) are computed as follow with starting conditions for this phase given by $\tau = (\tau_s)$, $i_e = (i_e)\tau_s$, $\int i_e d\tau = (\int i_e d\tau)\tau_s$, $(\frac{di_e}{d\tau}) = (\frac{di_e}{d\tau})_{\tau_s}$ being given by the numerical integration of the above two equations up to $\tau = (\tau_s)$ and at $\tau = (\tau_s)$ $i_2 = 0$, $\int i_2 d\tau = 0$ and $(\frac{di_2}{d\tau}) = \frac{(\int i_2 d\tau))(\tau_s) + (\frac{di_e}{d\tau})_{\tau_s}}{1+B_1+B_g}$. Then the values of $\frac{di_2}{d\tau}$, $\int i_2 d\tau$ and i_2 at $\tau = (\tau) + \Delta\tau$ are computed as:

$$\int i_2 d\tau = (\int i_2 d\tau)_{perviousvalues} + (i_2)_{perviousvalues}\Delta\tau + 0.5 * (\frac{di_2}{d\tau})(\Delta\tau)^2 \tag{3.1.3}$$

$$i_2 = (i_2)_{perviousvalues} + \frac{di_2}{d\tau}(\Delta\tau) \tag{3.1.4}$$

With these new values of current and charge, the value of $(\frac{di_e}{d\tau})$,and $(\frac{di_2}{d\tau})$ are now computed from equations (3.0.5),(3.0.6) and (3.0.7) respectively. Then these values of rate of rise of current the time may now be incremented to $\tau = (\tau) + \Delta\tau$ and the process repeated using MatLab program. The other quantities, such as voltages, power absorbed by laser gap are also computed after evaluating the currents rate and currents.

The following flow chart is used for the simple computation of the program to find the graphs of each of normalised amplitude verses normalised time. where $Q_1 = \int i_e d\tau$, $Q_2 = \int i_2 d\tau$, $R_1 = \frac{di_e}{d\tau}$, $R_2 = \frac{di_e}{d\tau}$ for $\tau \geq \tau_s$ $R_3 = \frac{di_2}{d\tau}$, T=τ, D=$\Delta\tau$, A=1+β_e, B=1+β_1+β_g


set scaling parameters
ae ,a1
set initial conditions
T= 0 , ie=0,Q1=0,R1=1/A,
T=Ts,I2=0,Q2=0,R2=(Q1+R1)/B
D=0.001
set time increment
N=0
print scaling parameters &
time increment
initialize counter
Print ae,print a1, print D
N=0
T=T+D
N=N+1
set time increment& counter
integrate for Q1,I &
Q2,I2 by linear
approximation
Q1=Q+I*D+0.5*R*D*D
I=I+R*D
Q2=Q+I*D+0.5*R*D*D
I2=I+R*D
compute new values rate
of currents R1,R2, R3 (Eq. 3.0.5-3.0.7
R1=(1-Q-ae*I)/(A)
A=179, B=28.2
R2=(1-Q1+Q2-ae*I+R1)/A
R3=(Q1-s*Q2-ae a1*I2+R1)/B
print the computed values
Print R, print I, print Q
Test,breakdown time (laser switching time)
T>Ts?
stop

Chapter 4

Results and Discussion

The following values of circuit elements are useful to study the electrical behaviour of the circuits which give some parameteric values and as a function of the two effective damping factors.

$$L_1 = 0.40\text{nH},\ L_2 = 0.18\text{nH}$$
$$L_{g1} = L_{g2} = 0.75\text{nH}$$
$$L_{g0} = 0.3\text{nH}\ ,\ C_1 = 100\text{nF}$$
$$C_2 = 50\text{nF},\ L_e = 32\text{nH}$$

The following Parameteric values are found from the ratios the above elements

$$\beta_1 = \tfrac{L_1}{L_2} = 2.2,\ \beta_e = \tfrac{L_e}{L_2} = 178$$
$$\beta_g = \tfrac{L_g}{L_2} = 10,\ \delta = \tfrac{C_2}{C_1} = 0.5$$
$$\text{where } L_g = L_{g1} + L_{g2} + L_{g0}$$

For maximum power transfer, one would hope to design the laser so that r_e has a value such that the spark gap circuit is fairly oscillatory; whilst, r_g should have a value such that the laser discharge circuit is nearly critically damped based on the following two tables which deteremine the these quantities with two cases.

α_e	α_{eff-e}	α_{eff-L}	α_1
5.40	0.4	3.0	3.61
2.67	0.2	2.0	4.90
1.34	0.1	1.4	6.60
0.27	0.02	0.1	2.4
0.40	0.03	0.2	3.4

Table 4.1: slightly damped, at $\alpha_1 = 6.6$

Case one: Laser gap crtically damped

Typical value of $a_{eff-e} = 0.1$ makes in the above table for which the external circuit is lightly damped. Thus, from Eq.(11), $a_e = 1.34$ since $\beta_e \sim 178$. Also, $a_{eff-L} = 1.4$ for laser gap critically damped. Using Eq.(12) and typical values of $\beta_1 \sim 2.2$, $\beta_g = 25$, and $\delta \sim 0.5$, yields $\alpha_1 = 6.6$.

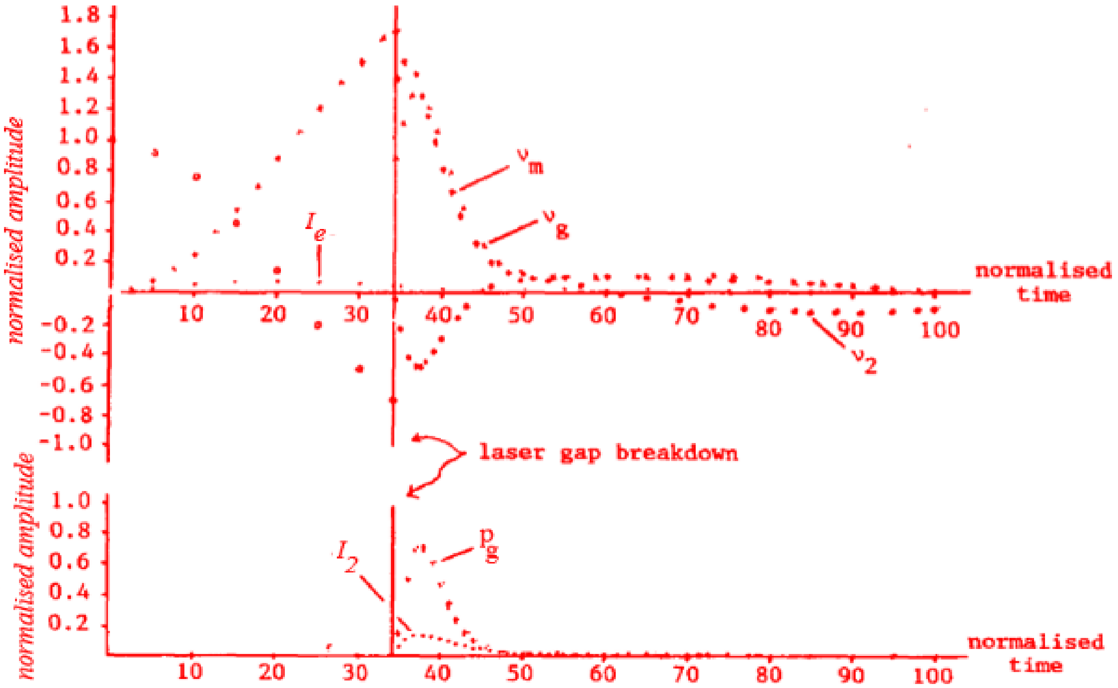


Figure 4.1: Variations in currents, voltages and laser gap power for $a_1 = 6.6$

Results for this case ($\alpha_1 = 6.6$) are presented in Fig.4.1. The voltage V_2 falls from 1.0 through $V_2 = 0$ at $\tau = 21.5$ to $V_2 = -0.7$ at $\tau = 34.5$ when the laser gap breakdown. On breakdown, the voltage V_2 rises sharply to -0.1. However, as I_2 rises quickly the voltage

V_2 drops once again to about -0.5 before rising again in a damped oscillation with periodic time of about 61to, as the capacitors C_1 and C_2 eventually discharge through the external spark gap. Between the time $\tau = 34, 1$ and $\tau = 51$, the laser gap current I_2 flows in its critically damped mode. The corresponding power goes up to a peak of about 0.7 in $38t_0$ and drops backdown with a FWHM value of $5.5t_0$.

α_e	α_{eff_e}	α_{eff_L}	α_1
1.34	0.1	0.40	1.7
1.34	0.1	0.30	1.5
1.34	0.1	0.25	1.2

Table 4.2: more critically damped, at $\alpha_1 = 1.7$

Case two: Laser gap effective damping factor of 0.4

Although the critically damped case may be the mode for optimazed power absorption by nitrogen laser, it became of interest to examine the performance behavior of the nitrogen laser system when subjected to 25 percent change, this is happend at $\alpha_1 = 1.7$.

This is physically obtained by increasing the spark gap to about four times as much as the size of the laser gap.

Results for this case ($\alpha_1 = 1.7$) on table 4.2 are computed and shown in Fig.4.2. In this case, V_2 also drops from 1.0 to -0.7 at $\tau = 34.0$, then rises sharply to zero on laser gap breakdown and continues with an oscillation of periodic time $\sim 17.5t_0$ superimposed on the slower periodic time of $\sim 70t_0$ of the external circuit. The laser gap current I_2 rises to a peak value of 0.25 in a time of about $40t_0$ and oscillates in a damped mode with a periodic time of$\sim 19.5t_0$ with modulation. The corresponding power developed across the laser gap resistance has a optimum value of 0.65 and a FWHM value of $5.0t_0$. For both cases above, the voltage V_m that may be measured across the laser channel (i.e. outside the laser channel) is shown in comparison to the actual voltage V_g.

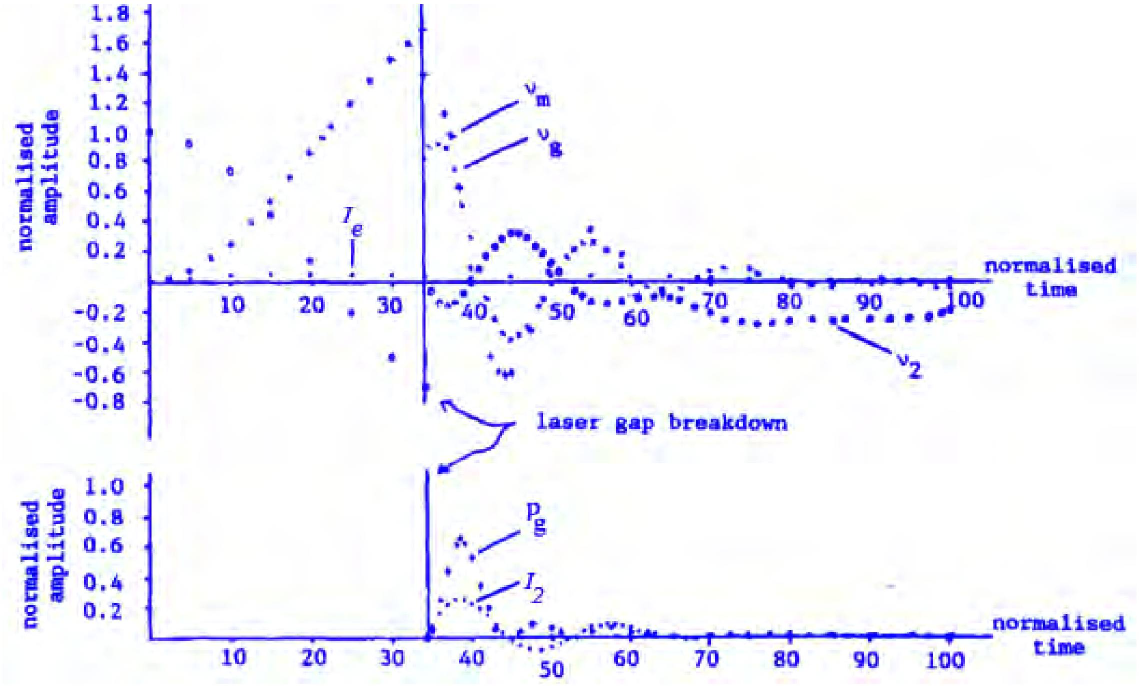


Figure 4.2: Variations in currents, voltages and laser gap power for $a_1 = 1.7$

From the above results the value of $dV_g/d\tau$ for a typical nitrogen laser may be estimated. We note that at a typical value of $t_o = \sqrt{L_2C_2}$ is 1.3ns. Operating voltage of 15kV, the average voltage $dV_g/d\tau$ is $\frac{(1.7\times 15kV)}{(34\times 1.3ns)} \sim 0.5kV/ns$. Such value is the first requiremen in the nitrogen laser discharge to initiate uniformity of discharge.

The difference in their values is due to the fact that the measured voltage includes the voltage drops across the channel inductances on either side of the laser gap.

Also, the variation in the laser spark gap current is also shown in fig.4.1 and 4.2

Chapter 5

Conclusion And Future Work

A parametric non-dimensionalised model for nitrogen laser circuit has been developed. This model is used to evaluate the the laser gap voltage, laser channel current and power absorbed for critically damped case and less critically damped case. The optimum power absorbed by this laser is around 70% for critically damped case. In future the model can be refined to include laser plasma parameters

Bibliography

[1] C. Iwasaki and T.Jitsuno, ‘an investegation of the effects of the discharge parametres‘ on the performance of AET N_2 laser, EEEJ. Quantum Electron, vol.18, pp. 423-427, 1982.

[2] S. Lee, A.V. Gholap, A.J. Smith, K.H. Kwek, A.C. Chew, T.Y.Tou, and S.sapru, ‘parametric study of Nitrogen laser’ vol.16 pp. 165-174 1985.

[3] T.mitani, ‘parametric study of the 357.7nm oscillation in TE (transversely excited) N_2 laser’, J.Appl.phys., vol.52, pp.3159-3166, 1981

[4] W.A. Fitzsimmons, L.W. Anderson, C.E. Riedhauser and J.M. Vrtilek, ’Experimental and theoretical investigation of the nitrogen laser.‘ IEEEJ.Quantum Electron., vol.QE-12, pp.624-633, 1976

[5] M. Csele ’Fundamentals of light sources and lasers‘, 1^{st} edition, (John Wiley & Sons, Inc., Hoboken, New Jersey), Canada, PP 267-298, 2004

[6] M. Montaser Foad.A.Hassen, M.Ewaida, ’the gas pressure in the nitrogen laser tube’ J.phys.E.Sci.Instrum,17, 103, 1984

[7] E. Gerry ’pulsed molecular nitrogen laser theory’, Applied physics Let. Vol.7, pp.6-8, 1965

[8] J.D. Shipmann.’traveling wave excitation of nitrogen power gas laser’. Applied phys.Let, Vol.10.10, pp.3-4 Jan.1967

[9] H.G. Heard, ‘Nature’ American Institute of Physics, Vol.200. pp 667, 1963

[10] A W.Alie, A.kobl and A.D Anderson ’theory of pulsed nitrogen laser system’ Applied

optics vol.6, pp.2115, 1967

[11] R.C. Elton, R.W.Wayant, Andrews, M.H.Reilly, 'A general rate equation analysis for three level laser UV laser system' Nava res.lab.Rep. 412, (1972)

[12] F. Kyeyune, 'Investigation of the Electronic Discharge Circuit of a N2 Laser' Laser Research Institute, Stellenbosch University, 2011

[13] W. T. Silfvast, 'Laser fundamentals', 2^{nd} edition, Cambridge University press, Pp 256-260, 2004

[14] B.Gondard 'a simple high power large efficiency nitrogen laser circuit theory UV laser'. IEEE Journal of Quantum Electronics. vol.12 1976.

Declaration

This project is my original work, has not been presented for a degree in any other University and that all the sources of material used for the project have been dully acknowledged.

Name:Mulugeta Setie

Signature:− − − − − − − − − − − −

Place and time of submission: Addis Ababa University, June 2012

This project has been submitted for examination with my approval as University advisor.

Name: Prof.A.V.Gholap

Signature:− − − − − − − − − −−