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P. Persephonis, B. Giannetas, R. Rigopoulos. A quadruple transmission line nitrogen laser. Revue de Physique Appliquée, 1983, 18 (5), pp.295-300. 10.1051/rphysap:01983001805029500 . jpa-00245094

HAL Id: jpa-00245094

<https://hal.science/jpa-00245094>

Submitted on 1 Jan 1983

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Classification

Physics Abstracts

42.60B — 42.55H

A quadruple transmission line nitrogen laser

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(Reçu le 15 septembre 1982, accepté le 17 février 1983)

Résumé. — On donne les considérations théoriques des avantages d'un laser à azote à ligne de transmission constitué de quatre plaques parallèles, comparé à un laser à double ligne de transmission. La vérification expérimentale montre que d'un laser d'azote à double ligne à un laser à quadruple ligne, il existe un accroissement de la puissance de sommet et de l'énergie par impulsion d'à peu près 50 % et 70 % respectivement. Les courbes expérimentales montrent l'accroissement de la puissance de sommet par rapport à la pression et à la fréquence de répétition. La ligne de transmission quadruple peut être utilisée dans n'importe quel laser à azote T.E., et dans d'autres laser à gaz à décharge.

Abstract. — Theoretical considerations on the advantages of a quadruple parallel-plate transmission line nitrogen laser comparatively to a double transmission line one are given. Experimental verification shows that from a double line N_2 laser to a quadruple one, an increase of the peak power and energy per pulse about 50 % and 70 % respectively exists. A common spark-gap is used. Experimental curves show the peak power increase *versus* pressure and repetition rate. The quadruple transmission line can be used in any other T.E. N_2 laser and other discharge gas lasers.

1. Introduction. — Nitrogen laser has been proved a necessary and useful tool for many applications in physics, chemistry etc... and it is widely used.

Among nitrogen laser designs there are many ones of simple construction and low cost [1-10]. The most common N_2 lasers are of transverse excitation (T.E.) with pulse electrical discharge. A transmission line (simple or double) is used as electrical energy storage capacity. Usually a Blumlein line with flat capacitors as transmission lines is used. The double line advantages against a simple one are shown from the experimental results of many authors as Fitzsimmons *et al.* [11].

It must be pointed out that further development in the design and construction of this category of N_2 lasers, in order to increase its power undoubtedly, would increase the possibilities for better investigation and analysis of problems which are faced at various applications frequently.

2. Theoretical aspects. — The problem of getting a high energy out of a N_2 laser is mainly the problem of putting a sufficiently large stored energy into the laser tube in a proper time duration. Theoretical studies and experimental data published up to day show that there is a complete dependence between the pulse laser performance and the electrical and geometrical characteristics of the circuit [10-17].

Figure 1 shows the equivalent circuit model of the Blumlein circuit used for laser excitation. In this figure S_1 and S_2 denote the gap-switch and the laser discharge channel respectively. Subscripts 1 and 2 designate the gap-switch side and the laser discharge channel side. So R_1 , L_1 , C_1 and R_2 , L_2 , C_2 are the resistance, inductance and capacitance of the circuits 1 and 2 respectively. Also I_1 and I_2 denote the discharge currents appearing on the gap-switch and the laser tube.

Fig. 1. — Equivalent circuit of a Blumlein N_2 laser.

The current I_2 regulates the laser output peak power and energy per pulse. The two last quantities i.e. laser peak power and energy per pulse, increase by increasing the peak value of the discharge current I_2 and decreasing its rise time [10].

The current I_2 is related to the electric field between the electrodes and consequently to the actual starting voltage by the relationship

$$E = \frac{1}{d} \left(I_2 R_g + \varepsilon L_2 \frac{dI_2}{dt} \right) \quad [11],$$

where ε is the ratio of the electrode separation d to the total perimeter length of the current flow in the tube, and R_g is the resistance of the discharge.

From the above relation it is clear that for higher peak value and shorter rise time of the discharge current I_2 , higher electric field, namely, higher actual starting voltage is needed. (This could be shown also by the relationship $KT_e = (E/p)^{0.8}$ eV with E/p in V/cm.torr [11] where K is Boltzmann's constant and p is the gas pressure. Higher actual starting voltage higher electron temperature T_e .)

The actual starting voltage increases by decreasing the anode voltage rise time [11, 13, 15, 16]. Naturally, this time depends on the resonant period of the circuit 1. Shorter the resonant period, $T_1 = 2\pi\sqrt{L_1 C_1}$, shorter the anode voltage rise time.

For constant capacitance C_1 the period depends on the inductance L_1 . Smaller inductance, shorter resonant period, shorter rise time of the anode voltage, higher the actual starting voltage and finally higher the output peak power and energy per pulse.

The energy stored at the capacitor C_2 of the circuit 2, plays, of course, its role. Stored energy can be increased (for constant applied voltage) by increasing the capacitor C_2 . Provided that other discharge parameters are kept the same, the laser output takes a saturated value when the capacitance of the voltage-side capacitor C_2 is in excess of the switch-side capacitor C_1 ($C_1 \leq C_2$) [10]. This reason makes necessary to increase C_1 together with C_2 . By increasing C_1 and C_2 together, the laser energy increases until a certain saturation value [10]. This is attributed to resonant period of the circuit 1, $T_1 = 2\pi\sqrt{L_1 C_1}$. By increasing the capacitance, T_1 increases for a constant value of the inductance, resulting to an increase of the rise time voltage across the laser electrodes. Consequently the actual starting voltage decreases. So, the increase of the capacitors value leads to saturation [10, 11, 14, 16, 18].

In order to conserve constant resonant period the inductance L_1 must be decreased with the same rate as the capacitor C_1 is increased. Then it would be possible that the output peak power and energy per pulse increase and the saturation is removed to larger C_1 and higher peak power of the N_2 laser.

In order to obtain a capacitance increase at the same rate of inductance decrease, we have thought to connect two double lines in parallel, namely, to construct a quadruple line. The quadruple line advantages against double one (with the same dimensions) are :

a) the capacitance is doubled,

b) the impedance is subdoubled, and naturally,
c) the inductance is subdoubled [3].

From b) the conclusion is that there is better matching to the impedance of the plasma load [1], while from a) and c) the conclusion is that the resonant period of the circuit 1, from double to quadruple line remains constant :

$$T_1 = 2\pi\sqrt{\frac{L_1}{2} \cdot 2C_1} = \sqrt{2\pi L_1 C_1}$$

and consequently the anode voltage rise time is constant too. So, the increase of the stored energy (because of the capacitance doubling) hopefully will result to an increase of the laser output.

On the other hand if for many reasons, we don't wish to increase the capacitance, we could replace a double line with a half length quadruple one. We can imagine that this can be done by cutting the double line capacitors at the half length and connecting the residual pieces of the capacitors to the laser tube. In this case the quadruple line has :

a) capacitance equal to double line one,
b) impedance half to double line one, and naturally,
c) inductance half to double line one.

1. From a) and c) the conclusion is that the rise time of the anode voltage decreases and consequently the actual starting voltage increases.

2. The discharge current I_2 , flowing in the laser discharge channel is closely related to the current I_1 , flowing in the gap-switch channel, which depends on L_1 and on the line impedance. Consequently from b) and c) the conclusion is that the current I_2 increases.

From 1 and 2 the final conclusion is that, with the same energy stored at the capacitors the output energy of the N_2 laser increases (for constant applied voltage).

However, in practice a N_2 laser, is not only composed of a line (simple-double or quadruple) but also a gap-switch is put necessarily at the one extreme of the line (usually a spark-gap) so the inductance L_1 of the circuit 1 is $L_1 = L_c + L_k + L_l$ where L_c is the constant gap-switch inductance, L_k is the time varying inductance of the gap-switch discharge channel and L_l is the stray inductance (plus all other distributed inductances). When the line from double becomes quadruple, the L_l is subdoubled, the L_k generally is decreased, because more charges pass through the gap-switch [19, 20], while the L_c value remains constant because the same gap-switch is used. Therefore, while total inductance L_1 is practically impossible to become subdoubled, however decreases significantly. The result of this fact is that the resonant period of the quadruple line is slightly increased comparatively to the double line. This has as a final result smaller output energy increase, than that expected if L_1 were subdoubled.

As mentioned above, the constant inductance L_c is an obstacle for subdoubbling the inductance.

When L_c tends to zero, the total inductance L_1 tends to subdoubling value which has as a result, when going from double to quadruple line, the resonant period is invariable. So from double to quadruple line a smaller inductance gap-switch will help the inductance L_1 to approach the subdoubling value and consequently a better output energy increase.

Our experimental results agree completely with the above theoretical aspects.

3. Experimental set-up. Measurements. — Our experimental effort is to compare results with double and quadruple line correspondingly of the peak power and energy per pulse in a N_2 laser.

Initially, a N_2 laser with a double parallel plate design, similar to the one reported by Basting, Schäfer, and Steyer [1] was built. The selection of this type was made without any particular preference except for the construction simplicity and low cost.

We believe that our experimental results don't reduce the generality of the application of the quadruple line in other types of (T.E.) lasers. The laser tube has 40 cm length. The electrodes are 1.5 cm apart and the gas flows transversely in the laser tube and is distributed uniformly in it. This is achieved by two parallel pipes placed along the laser tube so that the gas can get in and out through uniformly drilled pinholes [11].

The spark-gap is a triggered pressurised one with relative low inductance.

A plane mirror was placed at the one end of the laser tube in order to increase the outgoing radiation from the other end of it.

Epoxy circuit boards clad with copper on both sides were used as transmission lines and capacitors.

Board dimensions were : $L = 40$ cm (width), $l = 57.5$ cm (length) dielectric thickness $s = 0.9$ mm, and dielectric constant $\epsilon = 5.4$.

The impedance of the double parallel plate transmission line was calculated by

$$Z_2 = \frac{1}{2} \times \frac{Z_0}{\sqrt{\epsilon}} \times \frac{S}{L},$$

and was found equal to 0.1225Ω , where $Z_0 = 377 \Omega$, is the impedance of free space.

The capacitance of this transmission line was calculated similarly by the relation

$$C_2 = 1.11 \times \frac{2\epsilon}{4\pi} \times \frac{L \times l}{s},$$

and was found equal to 24.4 nF.

The length of the right triangle transmission line is

$$l_p = \frac{L}{2} \left(\sqrt{\epsilon} - \frac{1}{\sqrt{\epsilon}} \right) = 37.9 \text{ cm},$$

and it is determined by the condition that the time difference between the arrival of the voltage jump at

the far and near ends of the laser tube must equal the transit time of light travelling down the laser tube [1].

The capacitance of the triangle side is given by the relation $C_1 = 1.11 \times \frac{2\epsilon}{4\pi} \times \frac{L \times l_p}{2.S}$ and was found equal to 8 nF.

The laser beam was attenuated by a set of neutral density filters and was detected by a fast photodiode (ITT F 4018) and a Tectronix 7104 oscilloscope.

Figure 2 shows an oscillogram of a double parallel plate transmission line laser pulse.

Fig. 2. — Oscillogram of a double line laser pulse : applied voltage 12 kV, pressure 90 torr, repetition rate 5 Hz. Sweep speed 2 ns/div.

Consequently, another couple of similar boards was connected parallel to the initial one, see figure 3. In this way the double line became a quadruple one. The new boards were placed in such a way that each one of their surfaces was in contact with the internal surfaces of the initial boards. The electrical contact between the other surfaces of the new boards with the

Fig. 3. — Schematic drawing of the quadruple parallel-plate transmission line nitrogen laser. I. The initial double transmission line. II. The additional new couple boards.

external surfaces of the initial boards was achieved with appropriate links.

Measurements (with the same conditions) similar to the ones with only the double transmission line were made, for comparison of the results.

Figure 4 shows an oscillogram of a quadruple parallel plate transmission line laser pulse.

Fig. 4. — Oscillogram of a quadruple line laser pulse : applied voltage 12 kV, pressure 90 torr, repetition rate 5 Hz. Sweep speed 2 ns/div.

In figure 5, the laser peak power of a double and a quadruple transmission line is given as a function of the laser tube pressure, for different applied voltages.

The % increase of the laser peak power from the double to the quadruple line for different voltages with pressures corresponding to the maxima of the curves of figure 5, is given in table I.

The laser peak power percentage increase from the double to the quadruple line *versus* laser tube pressure for different voltages is given in figure 6.

Fig. 5. — Laser peak power *versus* laser tube pressure for one and two board couples.

Table I. — Increase (%) of the peak power as a function of applied voltage. Repetition rate 10 Hz.

kV	10	11	12	13	14	15
%	52.1	50.45	46.88	42.36	41.81	41.32

Fig. 6. — Percentage peak power increase from double to quadruple transmission line *versus* laser tube pressure for different voltages.

All the above measurements have been taken with 10 Hz repetition rate.

The laser peak power for double and quadruple transmission line as a function of the repetition rate for different voltages is given in figure 7.

The peak power percentage increase from double to quadruple line for different voltages with a repetition rate corresponding to the peaks of the curves of figure 7 is given in the table II.

The percentage increase from the double to the quadruple line as a function of the repetition rate for different applied voltages is given in figure 8. During

Fig. 7. — Laser peak power *versus* repetition rate for one and two board couples.

Table II. — Increase (%) of the peak power from double to quadruple line as a function of applied voltage. Repetition rate at maxima of figure 6.

kV	10	11	12	13	14	15
%	70	64.9	56.23	50.77	46.9	42.61

Fig. 8. — Percentage peak power increase from double to quadruple transmission line versus repetition rate for different voltages.

the measurements the laser tube pressure were equal to the maxima in the curves of figure 5.

The pulse duration (FWHM), as it is expected [11] decreases from 4 ns to 3 ns as the pressure increases from 35 torr to 130 torr for the double line, while for the quadruple line it decreases from 4.4 ns to 3.4 ns for the same pressure range.

As it was observed with the oscilloscope, the voltage difference at the laser tube electrodes is a damped sinusoidal oscillation with a large period compared to the laser lifetime. This confirms, experimentally, that the condition to generate a « travelling wave » [11], does not hold.

The voltage oscillatory periods were 45 ns for the double line and 50 ns for the quadruple one.

Finally the laser peak power was subquadrupled and pulse duration (FWHM) became about 2 ns when the plane mirror which was put at one end of the laser tube was removed.

4. Discussion. — Peak power and energy per pulse undoubtedly increases (see Figs. 2 and 4) when we add one more couple of boards.

The percentage increase to the peak power is about 58.8. A similar increase of the pulse duration was observed from 3 ns (double line) to 3.4 ns (quadruple line). Also, the increase in the energy per pulse was 80 %.

The increase in the peak power is affected by the laser tube pressure and the applied voltage. In figure 6 three areas are distinguished : a) pressure $p < 55$ torr; b) pressure $55 < p < 114$ torr; c) pressure $p > 114$ torr. At the extreme areas the higher the voltage the higher the percentage peak power increase, while in the middle area the higher the voltage the lower the percentage peak power increase.

The presence of the three areas can be explained as follows : at the high pressure area ($p > 114$ torr) the mean free path of the electrons is small and therefore, a strong electric field is required, so, it is possible that electrons acquire the necessary excitation energy during two successive collisions. When the pressure is small ($p < 55$ torr) the molecular number per volume is also small and this results in a reduction of the collision probability. In order to increase the pulse peak power in this area, excitation should take place during each collision. This requires high energy electrons, i.e. high voltage.

The percentage peak power increase from one to two board couples, varies also with frequency. In figure 8 the percentage peak power increase is decreased with voltage. This was expected because measurements shown in figure 7 were made by, middle area, pressures ($55 < p < 114$) where peak power increase is decreased with voltage.

The presence of maxima in figure 7 is explained by B. Woodward *et al.* [3].

The appearance of maxima in figure 8 is attributed to transposition of the quadruple line maxima to smaller frequencies, relative to double line maxima frequencies (Fig. 7). This transposition arises because in quadruple line there are more preionized atoms than in the double line.

Consequently for best discharge conditions longer time is needed for surplus charge removal, that is smaller frequency. Generally the peak power versus frequency, curve is affected strongly by the used spark-gap. By the parallel connections between the new and the initial boards, the capacitance of the system was doubled while the impedance was halved. So, the quadruple line capacitance becomes

$$C_1 = 2 \times 8 = 16 \text{ nF}$$

$$C_2 = 2 \times 24.4 = 48.8 \text{ nF}$$

and the impedance becomes

$$Z_2 = \frac{1}{2} \times 0.1825 = 0.09125 \Omega.$$

The inductance, L_1 , was determined by the formula

$$T_1 = 2\pi\sqrt{L_1 C_1},$$

where T_1 is the voltage oscillatory period measured with the oscilloscope.

L_1 was found to be equal to :

6.4 nH for the double line, and

3.96 nH for the quadruple one.

The slight increase of the resonant period from double line (45 ns) to quadruple one (50 ns) as and the nonsubdoubling (6,4 nH-3,96 nH) of the inductance are anticipated from the above mentioned theoretical aspects.

Finally, although we double the electrical energy at the capacitors (for constant applied voltage) from double to quadruple line, the laser peak power and pulse energy are increased by about 50 % and 70 % respectively. This increase is attributed to the slight increase of the resonant period, as was anticipated.

5. Conclusion. — The increase of the N₂ laser peak power and output pulse energy is not possible to be achieved by increasing the capacitance only. The quadruple line increases the capacitance and decreases the inductance, so that the rise time of the anode voltage remains nearly constant and the line impedance is subdoubled. So, an increase in the peak power and output energy is achieved.

The idea presented in this paper may be applicable to other types of T.E. N₂ lasers, or generally other types of discharge gas lasers too.

Our choice for this particular N₂ laser type was made without any particular preference and only for experimental verification of the idea without any restriction of its use.

Our experimental results showed an average increase of the pulse energy by about 70 %.

The fact that although doubling the electrical energy, the laser peak power and pulse energy are increased by about 50 % and 70 % respectively, is attributed to the spark gap or other switching system « quality ». Better quality spark-gap (small inductance) would result to a better percentage of peak power increase from one to two couples of boards.

Another advantage is the low cost when changing from a double line to a quadruple line. The cost corresponds to the additional couple of the board only.

A quadruple line half length from the double (all other dimensions are kept the same) has the same capacitance and stored electrical energy (for the same applied voltage) with the double one but better efficiency.

Generally the quadruple line idea is to put the electrical charge nearer to the laser tube and consequently the possibility placing additional charge.

Finally if we don't wish to increase the peak power and pulse energy we may use the quadruple line but with smaller applied voltages. So, we are released from additional insulation problems which are needed for higher applied voltages.

Acknowledgments. — The authors want to thank Mr. S. Koutsouvelis for his invaluable technical assistance.

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