PLASMA OSCILLATIONS IN A LASER

by

DANIEL C. GALEHOUSE

Submitted in Partial Fulfillment
of the Requirements for the
Degree of Bachelor of Science
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June, 1970

Signature of Author .

Department of Physics, June 4, 1970

Certified by . . . .

thesis supervisor

Accepted by . . . . .

Chairman, Departmental Committee on Theses
ABSTRACT

One type of noise in the argon ion laser is found to be caused by anode oscillations. It is shown that these can be removed by the use of a Pupp auxiliary cathode built into the laser tube. At pressures above 400 microns of mercury, no other oscillations have been observed within the operating parameters of the tube. At lower pressures, oscillations at approximately 170 kHz appear and are not removed by the Pupp discharge; however, these do disappear for sufficiently small values of the axial magnetic field.
**TABLE OF CONTENTS**

ABSTRACT .................................................. 2

TABLE OF CONTENTS ........................................ 3

TABLE OF GRAPHS, PLATES, AND DIAGRAMS ............ 4

INTRODUCTION .............................................. 5

ANODE OSCILLATIONS AND THE PUPP DISCHARGE TENT .... 7

OTHER OSCILLATIONS ..................................... 12

CONCLUSION AND SUGGESTIONS FOR FUTURE WORK ........ 17

ACKNOWLEDGEMENTS ....................................... 19

REFERENCES ............................................... 20

APPENDIX A -- Details of Anode Oscillations: Pressure dependence, Geometry dependent effects and Acoustical coupling. .............. 21

APPENDIX B -- Power Supplies .......................... 25

APPENDIX C -- Directional Light Detector .............. 34
# TABLE OF GRAPHS, PLATES, AND DIAGRAMS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1,</td>
<td>Anode Oscillation in the Discharge Current and Laser Beam</td>
<td>8</td>
</tr>
<tr>
<td>Figure 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Figure 3</td>
<td>Laser Tube Dimensions</td>
<td>10</td>
</tr>
<tr>
<td>Figure 4,</td>
<td>Axial Magnetic Field Dependence of High Frequency Oscillation Waveform</td>
<td>13</td>
</tr>
<tr>
<td>Figure 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Figure 6</td>
<td>Axial Field Dependence of the Frequency of the High Frequency Oscillations</td>
<td>15</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Axial Field Dependence of the Harmonic Content of the High Frequency Oscillation</td>
<td>15</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Pressure Dependence of the Waveform of the Anode Oscillations</td>
<td>22</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Pressure Dependence of the Frequency of the Anode Oscillations</td>
<td>23</td>
</tr>
<tr>
<td>Figures 10-17</td>
<td>Circuit Diagrams</td>
<td>26</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Directional Light Detector Dimensions</td>
<td>35</td>
</tr>
</tbody>
</table>
INTRODUCTION

There are several types of plasma oscillations which affect the light output of an argon laser. Some appear to be linear and perhaps, can be analyzed and removed with linear techniques. Others are strongly non-linear; some even seem to be relaxation oscillations. For this latter type, linear analysis is likely to fail in whole or part. The goal of this investigation is to begin to separate the different types of oscillations from each other. It is important to separate the effects experimentally, as well as theoretically. Data is more useful if it reflects exactly one type of instability.

According to Cooper and Cleeson there are at least two types of oscillations near the operating parameters of the argon laser—striations and anode oscillations.\(^1\) Striations have been shown to admit a linear solution for some operating parameters; however, anode oscillations have the characteristic of relaxation oscillations.

W. Pupp, in 1933, showed that anode oscillations in argon could be removed with an auxiliary cathode placed within a cylindrical anode.\(^2\) This method is found also to be effective in a modern laser tube. When the Pupp discharge is operating the anode oscillations are eliminated
and any remaining disturbances can be observed better.

Striations, however, have not been detected. This is reasonable because the argon laser is normally operated above the upper critical current for striations in argon.
ANODE OSCILLATIONS

Anode oscillations can be detected in the laser beam output intensity, in the sidelight emission, and in the discharge current. Examination of the oscilloscope traces shows that above the lasing threshold, the output intensity is a nearly linear function of the tube current. At threshold the waveshape is clipped on the lower side as would be expected.

The effect of an anode oscillation on the tube current and the light output is shown in figures 1 and 2. The first is an oscilloscope trace of the anode current, the second is a frequency analysis of the time dependence of the output beam.

The anode oscillation is composed of two parts: 1) a low frequency trapezoidal oscillation at approximately 2500 Hz, 2) a high frequency ripple at approximately 50 kHz which usually appears in that part of the low frequency oscillation where the average slope is negative. Sometimes it appears delayed from the region of negative slope.

The spectrum analyzer picture is essentially the amplitude of the fourier transform of the oscilloscope trace above it. The closely spaced spikes are at intervals
FIGURE 1. Alternating component of the laser tube current in the presence of an anode oscillation. Scale: 1.0 a/cm, Sweep: 0.1 ms/cm. The main discharge is operating at 10 amps.

FIGURE 2. Output of a Hewlett Packard spectrum analyzer operating from a solid state photodiode. Vertical scale: logarithmic 10 dB/cm, Horizontal scale 10 kHz/cm, Bandwidth: 100 Hz.
of the repetition frequency (2300 Hz). The humps at 30 kH, 45 kH, and 60 kH are the effect of the ripple oscillation. These have spikes superimposed upon them because for these particular operating parameters, the groups of 30 kH ripple oscillations are coherent from one repetition to the next. This effect is unusual. The humps at 30 kH and higher are in most cases smooth and without spikes because the pulse of the 30 kH ripples usually is not identical with each repetition. Appendix A discusses the anode oscillations in more detail.

A laser tube with both anode and cathode off-axis was modified by the addition of a Pupp cathode as shown in figure 3. The main discharge runs at currents from 6 to 13 amperes, the Pupp discharge runs at currents from 1.5 to 5 amperes. The Pupp discharge eliminates the anode oscillations at any of the above currents.

With the Pupp cathode heated by direct current no sign of the resumption of anode oscillations was detected as the Pupp cathode emission current was decreased to 1.5 amperes. Due to power supply limitations, the Pupp discharge was not operated below 1.5 amperes. Certain preliminary measurements were made with the Pupp cathode heated by alternating current at 60 Hz. In this case, higher currents (up to 4 amperes) were needed to
FIG. 3  LASER TUBE

1/3 SCALE

18 CM
4 OUTSIDE TURNS AT EACH VIEWING SPACE

2 CM
6.5 CM

3 MM. CAPILLARY

20 TURNS REPEATED 6 TIMES

2 LAYERS

36.5 CM.
57 CM.

AXIAL FIELD WINDING

588 TURNS TOTAL
45.2 TURNS PER INCH

WATER CONNECTION COOLING JACKET

VIEWING SPACES

MAIN CATHODE & SHIELD

ANODE

PUPP CATHODE
eliminate the anode oscillations completely. In lowering the emission current, anode oscillations first appear in groups at repetition rate of 120 Hz. The groups start

\[ \text{GROUPS OF ANODE OSCILLATIONS} \]

\[ \text{ANODE VOLTAGE} \sim 10 \text{V/cm} \]

\[ \text{REPETITION FREQ.} = 120 \text{Hz} \]

\[ \text{FREQ.} \sim 2500 \text{Hz} \]

with one anode pulse each and grow in steps of one pulse until a continuous string of pulses appears. The frequency of the anode oscillations within the groups does not change significantly as the length of the group increases. This supports the possibility that the oscillations are relaxation oscillations and that the operation of the Pupp discharge is to break the cycle. It shows as well that the Pupp discharge probably does not merely change the character of the oscillation but eliminates it altogether.
OTHER OSCILLATIONS

At pressures below 400 microns of mercury and for axial fields of 200 gauss or more, oscillations at frequencies from 200 kh to 150 kh were observed. The sidelight intensity shows that the oscillations are not localized to a small part of the tube. The frequency shows strong inverse dependence on the magnetic field. Since these operating parameters are near the limit of the laser tube and power supplies, it was only possible to carry out investigation with the axial field as a parameter. At an axial field of approximately 287 gauss and at a pressure of 300 microns of mercury the waveshape jumped discontinuously from one form to another. This is accompanied by a change in the light distribution of the tube and by a current pulse. Figures 4 and 5 show the oscilloscope trace of the anode current just below and just above the transition point. The two pictures were taken 5 gauss apart. This is not to imply that the transition occurs over that field change; the transition is sharp whereas the pictures were separated by 5 gauss only to make the waveform stable.

The transition point drifts slightly, probably due to power supply and line variation. The frequency jumps
FIGURE 4. Laser tube current. The axial field is operating at 12.75 amperes or about 285 gauss. Scale: 100 ma/cm, Sweep: 5 μs/cm. The Pupp discharge is operating.

FIGURE 5. Laser tube current. The axial field is operating at 13.0 amperes or about 290 gauss. Scale: 100 ma/cm, Sweep: 5 μs/cm. The Pupp discharge is operating.
discontinuously 22.5 kHz downwards as shown in figure 6. The waveshape change from figure 4 to figure 5 suggests that the second harmonic of the fundamental is causing the change. The laser light output was again put into a spectrum analyzer. The peaks are extremely sharp and easily identifiable. The intensities (on a logarithmic scale) of the fundamental, second and third harmonics is plotted in figure 7. At the transition, the intensity of the second harmonic drops by more than a factor of 10 while the fundamental decreases by only a factor of 3.

The results are difficult to interpret without having more data at lower pressures and higher currents. Oscilloscope observation indicates that the actual change in the amplitude of the modes is small, no more than a factor of two or three. In the region above 325 gauss, the increase in the second harmonic might be due to nonlinear limiting effects as the oscillation increases in amplitude. The transition reflects a change in the combination of modes that are oscillating. Changes in the waveshape below the transition show that the oscillation is composed of two modes coupled in a weak way. The waveshape is sometimes triangular and sometimes rising or falling sawtooth. Below the transition, the oscillations are composed of a mode at the fundamental frequency and a mode at the second
harmonic. The increasing magnetic field suppresses the mode at the frequency of the second harmonic.
CONCLUSION AND SUGGESTIONS FOR FUTURE WORK

This work supports the conclusion of W. Pupp that the secondary cathode can be effective in stopping anode oscillations. Even when the tube geometry is constrained by the requirements for lasing operation, the method is effective.

The motivation for studying these plasma problems comes from the goal of a noise free argon laser. It is important to study these particular oscillations since they are present; however, in this experiment, the laser light itself has provided little information beyond what has been obtained from other measurements. The oscillations could be more easily studied in a tube designed solely for the particular oscillation at hand and without the geometrical restrictions of a laser tube.

The investigation of the particular oscillations reported here could be continued along several directions. The Pupp cathode has possibly never been tried as a cold cathode. According to Pupp's article, the elimination of anode oscillations is accomplished by the production of ions at the anode. Any method of producing ions might be effective in removing anode oscillations.
With reference to both types of oscillations reported here, the effect of the output impedance of the power supply has not been determined. The supply circuit used here could not be changed because of the limited line supply voltage and the requirement of low line ripple. The oscillations do depend on the real and complex parts of the supply output impedance. An investigation of this dependence might help explain the mechanism of the oscillations.
ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Professor Uno Ingard for the discussions from which this project arose and for his help and direction throughout the project. I am indebted to Professor Weiss and Professor Ezekiel for explaining the operation of lasers and for the use of their shop in constructing equipment.

This work was supported in part by the U. S. Army, the Air Force Office of Scientific Research, and the Office of Naval Research through the Research Laboratories of Electronics.
REFERENCES


2. W. Pupp, Physik. Z. 34, 756 (1933)

General background in Plasma Physics:


Von Engle, Ionized Gases, Oxford (1955)

General background in lasers:


More recent investigation has shown that the oscillations described in pages 12 through 16 are of the type discussed in these articles:


Lehnert, Phys. Rev. Lett. 5, 409
Pressure dependence: Figure 8 shows the waveform of the anode oscillations at different pressures. With the power supply configuration of page 30, the pulse repetition frequency decreases with pressure and the ripple frequency increases with pressure. This higher frequency component was not reported by W. Pupp. If it was present in his discharge tube, it was probably beyond the frequency response of his apparatus. At pressures below 400 microns of mercury, the two frequencies become nearly equal and the two parts of the waveform become less distinct. These two frequencies are plotted in figure 9.

Geometry dependent effects: Sidelight intensity measurements show that variations along the tube are small except at the anode. Variations near the anode are large and come from bright regions called spots. It is known that these spots are related in number and position to the discharge current and anode geometry. At certain pressures in the laser tube, the glowing column splits into two parts just in front of the anode. The light comes in pulses which alternate in their origin between the two spots. The pulses from either branch alone are evenly spaced and both branches have the same spacing. The two branches, however, are not synchronised exactly. The pulses from one branch often
FIGURE 8
WAVEFORM OF ANODE OSCILLATIONS AT DIFFERENT PRESSURES. SUPPLY USED IS THE ONE ON PAGE 30 (HIGHLY CAPACITATIVE OUTPUT IMPEDANCE). THE PLOTS HERE ARE OF THE CURRENT FLOW THROUGH A .1 Ω RESISTOR IN THE ANODE LEAD. THE SCALE IS ONE AMP. PER CM. ALL WERE TAKEN WITH A DISCHARGE CURRENT OF 10 AMPS FLOWING.
appear leading or lagging by several percent from exact alternation. This is easily seen on the oscilloscope screen since the trace is triggered by the first pulse. Odd numbered pulses appear stationary while the even numbered pulses wobble about their average position. Usually at higher pressures, three or more spots appear. Sometimes the light emission cycles regularly from one spot to another. In other cases, the flashes come more or less incoherently.

Possible Acoustical Coupling: The repetition rate of anode oscillations is in the audio range. A resonance like effect can be heard at certain frequencies by listening in the anode area. Since the current in the tube and the other parameters do not change when passing through one of these resonances, it is possible that there is a coupling from the plasma to the acoustic field. There is also a sound that comes from the power supply current limiting resistor which is, perhaps, confused with this sound.
APPENDIX B — POWER SUPPLIES
AXIAL FIELD SUPPLY
OUTPUT 20A D.C. AT 20 V D.C.

VARIAC
630 V.A.

FUSE, 10A

BLACK
GREEN
WHITE
LINE CORD & GROUNDED PLUG

(2) UTC TRANSF.
14V, 10A

(2) FIL. TRANSF.
6.3V, 10A

(4) IN248A

.024 HY. 20A

.032 F 40V.

.032 F 40V.

390Ω 2W

0-30V SHOULDBE 0-20A

0-15V SHOULDBE 0-30V

+ -
MAIN FILAMENT SUPPLY
TRANSFORMER SECTION
A.C. OUTPUT CONNECTION 0-30A.
TERMINAL CONNECTIONS:
1. LINE CORD AND GROUNDED PLUG
2. (2) TRANSFORMERS SEC. 12V, 30A.
3. CHASSIS GROUND
4. A.C. CENTER TAP
5. A.C. OUTPUT
6. A.C. OUTPUT
TO RECTIFIER SECTION
MAIN FILAMENT SUPPLY

RECTIFIER SECTION
D.C. OUTPUT CONNECTIONS 0-30A
TERMINAL CONNECTIONS:
1. D.C. POSITIVE OUTPUT
2. D.C. NEGATIVE OUTPUT

FROM TRANSFORMER SECTION

(4) IN248A

(6) 0.45Ω C.T.
160 W

.05F
40 V.

390 Ω
2W

.05 F
40 V.

500 Ω

2500V VARIABLE

.2 MΩ

.5 MΩ VARIABLE

50μF
25V

ZN3906

ZN442

THIS OUTPUT SECTION IS INSULATED TO FLOAT ABOVE CHASSIS GROUND POTENTIAL 0-30 A.D.C.
SECONDARY FILAMENT SUPPLY

ALTERNATING CURRENT OUTPUT
6.3V, 20A MAX.

FUSE, 5A

BLACK
GREEN
WHITE
LINE CORD & GROUNDED PLUG

VARIAC 630V.A.

PANEL LAMP

(2) FIL. TRANSF.
SEC. 6.3V, 10A

0-30 A. A.C.

A.C. OUTPUT

CENTER TAP

THIS SUPPLY MAY BE CHANGED TO D.C. EITHER WITH A CHOKE IN THE STYLE OF THE AXIAL FIELD SUPPLY OR WITH MORE TRANSFORMERS IN THE STYLE OF THE MAIN FILAMENT SUPPLY.
MAIN DISCHARGE SUPPLY AS RIPPLE FILTER

(2) .2 HENRY 7.55 A.

(2) 1100 μF 150 V

5Ω 23A

OPTIONAL CHOKE .024 HY, 20A
MAIN DISCHARGE SUPPLY OPERATING FROM 3-PHASE A.C.
DISCHARGE CONTROL
FOR 2 INDEPENDENT
DISCHARGES

TERMINAL CONNECTIONS:
1, 2 SEC. DISCHARGE
SERIES RESISTOR
3, 4 OUTPUT TO
SEC. DISCHARGE
5, 6 OUTPUT TO
MAIN DISCHARGE
7, 8 MAIN DISCHARGE
SERIES RESISTOR

IF SERIES RESISTORS
ARE CONNECTED INTO
ANOTHER PART OF THE
CIRCUIT, TERMINALS
1, 2, 3, 4, 5, 6, 7,
AND 8 SHOULD EACH
BE SHORTED.

MI, M2, S1, AND S2 ARE
CONNECTED TO THE
STARTING CIRCUIT.

D.C. PLUG AND 15' OF CORD
(2) PANEL LAMPS
(2) FUSES 15A
6 ANODE

D.C. PLUG AND 15' OF CORD
(2) PANEL LAMPS
(2) FUSES 10A
3 ANODE
STARTING CIRCUIT
MOUNTED ON THE CHASSIS
OF THE DISCHARGE CONTROL
BOARD

(3)-300V
BATTERIES

1M
10\mu F

M1

S1  S2

TEMPORARY STARTING
CIRCUIT

FUSE, 1A

2000V MIN
TOTAL P.I.V.

MIN. SUM
100 KΩ

700 V.A.C.
10 MA.

10\mu F
1000V

A.C. PLUG
WITH GROUND

PANEL LAMP

(4) IN3495

DESIGN FOR HIGH VOLTAGE
STARTING WITHOUT BATTERIES

M1

S1

S2

M2
APPENDIX C — DIRECTIONAL LIGHT DETECTOR
DIRECTIONAL LIGHT DETECTOR

SIDE VIEW