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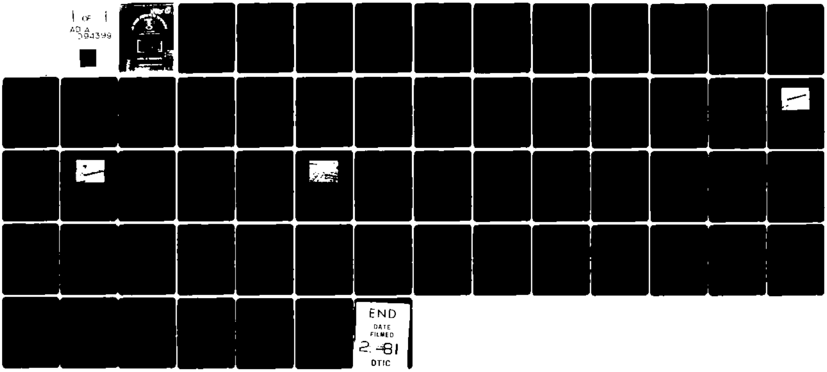

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A DISC-LOADED MICROWAVE GUIDE
FOR LASER APPLICATIONS

THESIS

AFIT/GEP/PH/80-11 Michael B. Tutin
Captain USAF

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THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by

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PREFACE

This investigation represents a very small part of a concerted effort at the Air Force Avionics Laboratory to develop effective laser systems for Air Force applications. Microwave power is readily obtainable for airborne use and is easily handled. A microwave-pumped laser would also not have the electrode degradation and contamination problems associated with other systems. Therefore, lasers excited by microwaves show definite potential, but, to date, research in this area has been limited. This study was suggested by Dr. W. Schuebel of the Avionics Lab to determine the suitability of a disc-loaded microwave cavity for laser applications. While the disc-loaded microwave cavity has been used elsewhere, its usage in a laser system is unique.

Special thanks are due to Dr. Schuebel for his idea and sponsorship of the project. Dr. E. Dorko of the Air Force Institute of Technology and J. Brandelik of the Avionics lab also suppled invaluable aid. I would also like to acknowledge the timely and precise work of Mr. J. Brohas, who fabricated the cavity, the skill of Mr. S. Derby who supplied a lot of the technical expertise for the project, and the expert glassblowing of Mr. R. Wade.

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ABSTRACT

A brass disc-loaded microwave cavity was built and the feasilibity of using it as the pump for an argon ion laser was investigated. The cavity was 3 feet long and its insertion loss was measured to be 6.3 db. The voltage standing wave ratio for an empty cavity was found to be below 1.5 at all frequencies from 2425 MHz to 2475 MHz. A quartz laser tube was inserted in the microwave cavity and filled with .50 torr of argon. A uniform discharge was obtained with 180 W of input power, and a spectral analysis revealed that previously known laser transitions occurred in the discharge. A laser cavity was formed, and a "fireball" was observed in the discharge. However, attempts to optimize the system to obtain lasing were not completed. It was concluded that improvements must be made to the cavity to decrease the insertion loss and to the power supply to more effectively couple power to the plasma.

A DISC-LOADED MICROWAVE GUIDE FOR LASER APPLICATIONS

I. INTRODUCTION

The pumping of lasers with microwaves is a promising development in laser research. The process has many advantages over other excitation methods, such as the dc discharge, and has been investigated by several authors (Refs 1; 2; 3; 4; and 5). They all point out that the electrodeless configuration of the microwave discharge eliminates contamination problems. In addition, it is felt that the higher electron temperatures found in microwave discharges lead to greater efficiencies for lasers. These hypotheses have been tested (Refs 1; 3; and 5); but, while a solution to the contamination problem has been demonstrated, increases in efficiency have not been substantial enough to warrant an abandonment of traditional excitation methods.

The design of the waveguide for the microwaves may be the key to increasing laser efficiency. Most of the previous researchers in this area have utilized rectangular waveguides to excite the laser medium. A disc-loaded radial waveguide yields higher electron energy distributions (Ref 6:196) than a rectangular waveguide, and, therefore, should lead to higher efficiencies. A circular waveguide also has a greater power - handling capacity (Ref 7:97) which would be important for high energy laser applications. In short, the construction and testing of a disc-loaded microwave guide for laser applications is definitely warranted by the above and is the basis for this investigation.

BACKGROUND

The development of radar and microwave technology in the 1940's led to the consideration of microwaves as a source for exciting plasmas. Brown and others advanced the theory of microwave discharges for applications in the fields of plasma chemistry and spectroscopy (Refs 8 and 9). Maksimov suggested the use of microwaves as the pump for a gas laser in 1966 (Ref 10:422). However, most of the research to date on gaseous lasers has been conducted with dc discharges.

A comparison of dc discharge lasers and microwave discharge lasers is instructive. Muller *et. al.* have summarized the disadvantages of a dc discharge laser (Ref 4: 1012-14). First of all, lasers pumped by dc discharges have low efficiencies. George (Ref 2:1152) attributes this to the steady - state electron energy distribution in the dc discharge. This distribution is characterized by large electron densities at low energies which do not significantly contribute to upper laser level excitation. A second disadvantage is the high voltage required for a dc discharge, which makes it difficult to construct portable systems and increases warm-up time. Finally, under the influence of high voltage, the electrodes decay. This phenomenon reduces the life of the laser, and also introduces contaminants into the plasma. This contamination can quickly stop the lasing process, especially in metal halide lasers. In short, while dc discharge lasers have found wide-spread use, there are severe shortcomings in these systems.

Gaseous lasers that are pumped by microwaves do not have these problems. Again, Muller et.al. and others have theoretically argued the advantages of a microwave-excited laser. The microwave discharge is stable and has a higher energy density than a dc discharge. This stability makes it possible to utilize the pump energy more efficiently (Ref 4: 1014).

The use of microwaves can theoretically improve the parameters of gaseous lasers. Increasing the electron temperature of the plasma under steady - state conditions increases the efficiency of the laser and the microwaves do this with a non-Maxwellian energy distribution (Ref 4: 1013). Microwave discharges are also electrodeless, thus eliminating electrode degradation and contamination problems (Ref 1:7). Compact, portable systems may also be constructed using transistorized microwave elements.

OBJECTIVE

The above discussion clearly illustrates the desirability of utilizing microwaves as the pump for gaseous lasers. The purpose of this investigation was to construct a disc-loaded microwave guide and to test known laser species in the system. The basic design of Van Koughnett et.al. (Ref 6:197-209) was used in the design for the microwave cavity, and the laser gases chosen for study were helium (for use in a helium-cadium laser) and argon. These species were picked because much is already known about them and comparisons can readily be made with existing laser systems that utilize these same species but different excitation mechanisms.

II. THEORY

The theoretical aspects of this experiment will be discussed in this section. First, the design advanced by Van Koughnett et. al. for the microwave cavity will be validated. To accomplish this, the basic mechanism of the microwave discharge will be explained, and some elementary waveguide theory will be introduced. Secondly, the spectroscopy required to understand the laser applications of the cavity will be outlined. The processes in the helium-cadmium mixture will be emphasized.

CHOICE OF THE CAVITY

The design of Van Koughnett, Dunn, and Woods was employed in this study (Ref 6:197-204). In their article these researchers have given the theoretical foundation for the cavity design and their development will be paralleled and expanded here. However, the operation of a general microwave discharge system will first be covered, and will be followed by a short description of slow wave electromagnetic systems.

McTaggart has succinctly described plasma excitation in electrical discharges (Ref 11:15). A discharge results when free electrons are accelerated in an electric field until they attain sufficient energy to cause ionization or excitation of some of the gas molecules in the plasma. Depending upon the energy levels of the gases and the electron energy distribution, various excited states (including upper laser states) of the atoms and molecules may be created.

The advantages of a microwave discharge over a dc discharge have already been enumerated, so the remaining problem is the choice of the geometry for the microwave cavity. Previous workers in the field have utilized only rectangular waveguides for the microwaves. Muller et.al. have built a helium-neon (He-Ne) microwave-excited laser (Ref 5:1302-1303). They used a very short gain medium (4cm long) and a 27V power supply for the microwaves, thus demonstrating that a compact, portable system could be built. They achieved a power output of .25mw, which compares favorably with other systems, and hypothesized that vast improvements could be made.

Handy and Brandelik have reported on microwave excitation of a pulsed CO_2 laser (Ref 3:3755). They found a 0.7% increase in efficiency when a microwave discharge was used instead of a dc discharge. This increase is not trivial as the efficiency of CO_2 lasers is usually less than 25% (Ref 12:81).

The above work demonstrates that microwave excitation can yield definite improvements in the parameters of gaseous lasers. However, it is not clear that a rectangular waveguide geometry is necessarily the best for efficiency. Asmussen et.al. have stated that these systems are generally restricted to small plasma volumes and low pressures (Ref 13:109). In addition, such structures are characterized by non-uniform fields and are very difficult to analyse electromagnetically.

A circular waveguide does not have these undesirable characteristics. It has a greater power handling capacity and a lower attenuation than a rectangular waveguide. However, a hollow circular guide will not effectively couple the microwave energy to the plasma. To do this, one must employ some type of slow wave structure. A slow wave structure makes the wave velocity of the microwaves approximately equal to the velocity of electrons in order that the electric field of the wave will travel with the electrons and accelerate them (Ref 14:VII). In other words, a slow wave structure slows down the microwaves so that their energy may be coupled to the electrons.

Bevensee details one slow wave structure, the periodic cavity-chain shown in Figure 1. (Ref 14:5-14).

He states that the electric field in the z direction, E_z, may be written as

$$E_z(r,\Theta,z) = V_m(z)\bar{e}_{mz}(r,\Theta) \qquad (1)$$

$$V_m(z+L) = V_m(z)e^{-jB_oL}$$

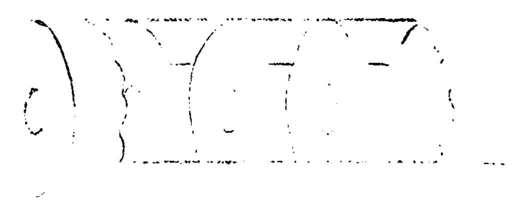

Figure 1. Periodic Cavity-Chain Structure

where B_o is the propogation constant of the wave, $\bar{e}_{mz}$ is a waveguide mode pattern of a circular waveguide, and $V_m(z)$ is a complex amplitude. This amplitude can be expanded in a Fourier series as

$$V_m(z) = \sum_{-\infty}^{\infty} V_{mn} e^{-jB_n z + jwt} , \quad B_{\theta} = B + \frac{2n}{L} \qquad (2)$$

where w is the frequency of the wave.

These equations can be used to solve Maxwell's equations in the cavity chain, and, therefore, determine the energy coupling of the structure. However, that development requires a detailed mathematical formalism, and will not be pursued here. Bevensee does give the Marcuwitz-Schwinger technique and the resonant cavity mode technique for obtaining solutions(Ref 14:27-36). In this instance, a common sense analysis does yield a useful feel for the processes in the structure. The discs in Figure 1. would slow a stream of water coursing in the pipe. In the same way, microwaves are slowed, and electrons may then absorb power from them (Ref 14:2). These power gains from the electric field can be tremendous even over short interaction lengths.

Asmussen et. al. have developed a cylindrical waveguiding system which is able to sustain a plasma (Ref 13: 109-117). It consists of a plasma cavity terminated at one end by a fixed short and at the other by a variable short. The microwave power is coupled to the resonances of the plasma cavity by physical tuning of the variable short. This system was used to investigate chemical reactions in microwave discharges but Asmussen et. al. also stipulated that it could be used as an active plasma for a laser.

A different cylindrical geometry has been proposed by Van Koughnett, Dunn, and Woods (Ref 6:195-209). They designed a disc-loaded circular waveguide structure as an applicator for microwave heating of filamentary materials. This system consisted of periodic cylindrical sections with irises that form a disc-loaded structure and two identical transition and transformer elements, as illustrated in Figure 2. The authors state that this structure yields a

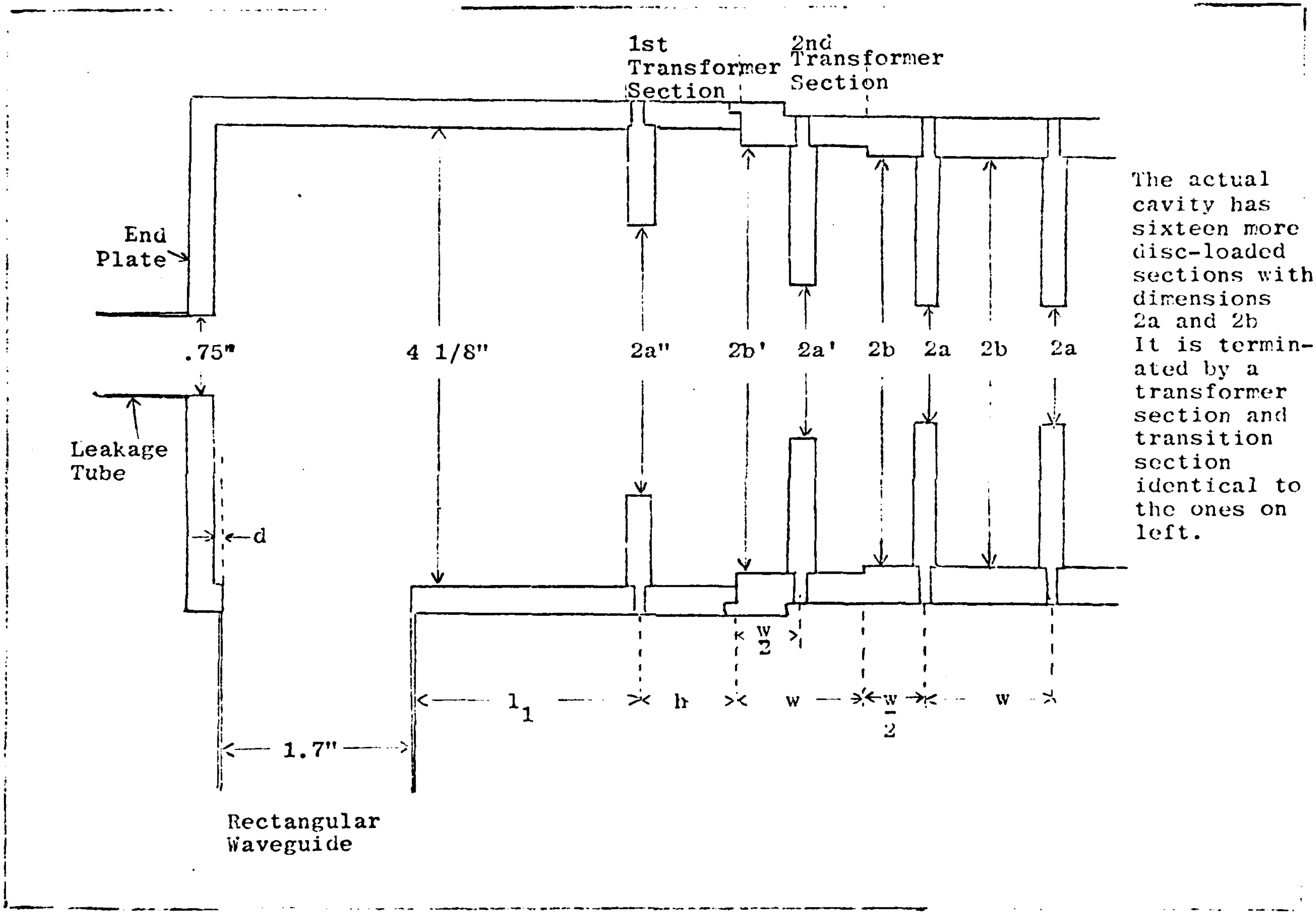

Figure 2. Side View of The Feed Section of The Disc-Loaded Cavity.

uniform field distribution throughout the cross section of a cylinder approximately one inch in diameter for a 2450 MHz applicator and also is very efficient. These factors and the relative simplicity of the disc-loaded section make this cavity an attractive candidate for use in a laser system. The filament in Figure 2 would be replaced by a laser tube, which would also have appropriate Brewster windows and mirrors aligned to it. The system would be mechanically complex, but would have the advantages already mentioned for cylindrical systems.

CAVITY CHARACTERISTICS

The geometry of the microwave cavity depicted in Figure 2 on page 10 must be completely specified to achieve the desired results. The first requirement of the system is that a uniform field exist throughout the cross section of a cylinder. The TM_{01} mode of a circular waveguide meets this requirement and is shown in Figure 3.

Since each mode of a circular waveguide has a cut-off wavelength which is a function only of the inside diameter, the diameter 2b is chosen such that only TM_{01} and TE_{11} modes are possible (Ref 15:61). The TE_{11} mode is then suppressed by a method which will be discussed later.

The next step is to determine the dimensions of the disc-loaded section. Given an operating frequency of 2450 MHz, one would necessarily want this frequency to correspond

Figure 3. The TM_{01} Waveguide Mode

to the center of the passband of the structure. To accomplish this, the dispersion relation (Ref 14:102) for a disc-loaded cavity is used,

$$f = (f_2+f_1)/2 - 1/2(f_2-f_1)\cos Bw \quad (3)$$

where f_2 and f_1 are the upper and lower cut-off frequencies of the passband, Bw is the phase shift per period of the structure, and w is the period of the structure as shown in Figure 2 on page 10 (Ref 6:196). For f=2450 MHz to be the center of the passband, Bw must equal $\pi/2$ at this frequency. Also, for the longitudinal component of electric field to be uniform over the diameter of the cavity, the phase velocity of the disc-loaded structure must equal the free space velocity c. Therefore, at 2450 MHz,

$$Bw = 2\pi w/\lambda_o = \pi/2 \qquad (4)$$

where λ_o is the free space wavelength = c/2450MHz. This leads to $W=\lambda_o/4$ = 1.204 inches.

The fact that the phase velocity equals c also helps to determine the diameter 2a of the hole in the discs. Walkinshaw (Ref 16:248) gives the peak longitudinal component of electric field E in the disc hole diameter as

$$E = \lambda_o\sqrt{480P}/\pi a^2$$

where P is the RMS value of the power flow along the structure. Van Koughnett <u>et. al.</u> arbitrarily limit E to 3000 volts/cm to avoid breakdown problems, and with a power level of P=5KW, equation (5) indicates that 2a cannot be less than 1.1 inches to achieve maximum coupling.

Walkinshaw also developed the theory for determining the diameter 2b (Ref 16:248). Using his results, Van Koughnett <u>et</u>. <u>al</u>. theoretically obtain 2b= 3.810 inches for f=2450 Mhz. However, they also determined this value experimentally by finding resonances of a two period disc loaded section. The value 2b = 3.791 inches was used by them. Therefore, all of the dimensions of the disc-loaded section have been determined, but the transitions to and from it must still be specified.

Standard rectangular waveguide can be used to carry the microwaves to and from the cavity. Ragan (Ref 17:380) gives the method for deriving a transition from rectangular waveguide to TM_{01} mode circular waveguide. For a 4 1/8 inch circular guide, Van Koughnett et. al. measured the radiation pattern of the antenna formed by an open-ended circular waveguide and adjusted d to yield a null in the direction of the circular waveguide axis. This suppresses the TE_{11} mode and only TM_{01} mode propagation is possible. The value of d obtained in their experiment was .060in.

Finally, the last requirement is a transformer section to match the TM_{01} mode waveguide to the disc-loaded section. The characteristic impedances of the two sections differ drastically, so the transformer section will be somewhat complex, as shown in Figure 2. Van Koughnett et. al. basically designed the transformer as a two section quarter-wave transformer. The second transformer section with dimensions 2a' and 2b' will give a phase shift of 90° if those dimensions yield a characteristic impedance of $Z_o^{3/4}$ where Z_o is the characteristic impedance of the disc-loaded section. They measured Z_o and then stipulated that the characteristic impedance varies as a^4, where a is the radius of a disc. Therefore for two different discs

$$(a'/a)^4 = Z_o^{3/4} \qquad (6)$$

Since they experimentally measured Z_o to be 2.66, Eqn (6) yields 2a' = 1.4 inches. The required value of 2b' was determined to be 3.880 inches by the same method employed to find 2b.

The remaining transformer section must complete the impedance match, and, therefore, have a characteristic impedance of $Z_o^{1/2}$. However, previous errors and imperfections of the system make a theoretical determination of the first transformer section parameters impractical. Instead, Van Koughnett <u>et</u>. <u>al</u>. determined h and 2a" experimentally to insure the best impedance match.

The above discussion completely defines the geometry of the microwave cavity except for h and 2a". In their application of heating filaments, Van Koughnett, Dunn, and Woods state that the cavity promises stronger coupling, a more uniform heating cross-section, and higher efficiency than other waveguide geometries. These same advantages hold great promise for use of the cavity in a laser system.

<u>MICROWAVE-PUMPED LASERS</u>

Some advantages of microwave discharge lasers have been enumerated above, and various work in this field has been cited. Still, it is not clear that microwave pumping of lasers provides overwhelming advantages over other systems. The few microwave laser systems mentioned in the previous discussion demonstrated the feasibility of this excitation method, but the obtained results do not warrant an abandonment of traditional excitation methods.

It is also not clear what types of laser systems are best-suited for microwave excitation. Chemical, ion, and metal vapor lasers are all possibilities, but it has not yet been established which particular system would best use microwave excitation. This investigation, with the use of the unique waveguide structure, yields at least a partial solution to this problem.

An essential factor for the utility of the microwave discharge is its electron energy distribution function. An experimental determination of this function would be ideal, but, unfortunately, is beyond the scope of this work. However, an indirect indication of the form of the electron energy distribution function can be obtained by comparing the available experimental results with previous data from hollow cathode discharge (HCD) work. The electron energy distribution function for a HCD in helium has been measured (Ref 18:84), and was found to be strongly non-Maxwellian with a high concentration of high-energy electrons. Schuebel found six new CW laser lines in a helium-cadmium HCD and attributed them to this non-Maxwellian electron energy distribution function (Ref 19:574). These lines (5337 Å, 5378 Å, 6335 Å, 6360 Å, 7237 Å, 7284 Å) have not been found in positive column discharge lasers, which are characterized by Maxwellian distributions. Therefore, if it can be shown that these transitions occur in a microwave helium-cadmium system, it may logically be inferred that the microwave discharge distribution function is non-Maxwellian with a high concentration of high energy electrons.

The measurement of the spontaneous emission spectra of any discharge provides a relatively simple method for roughly determining excited state populations. For instance, the spontaneous emission spectra of helium and argon can be measured for a microwave discharge as a function of the input microwave power, the gas pressure, and the plasma tube bore. In this way, the optimum configuration for argon and helium-cadmium lasers that are pumped by microwaves may be determined. Once these configurations are found, the important parameters of these lasers, like efficiency and wavelength, may also be measured. This data base can then be used to draw conclusions about the suitability of further microwave excitation studies.

III EXPERIMENTAL APPARATUS

The experimental apparatus will be described in this section in two parts. First, the microwave cavity and associated microwave components will be described. Secondly, the laser application components, including the vacuum system and discharge tube, will be listed.

MICROWAVE COMPONENTS

The microwave cavity design of Van Koughnett *et. al.* was used in this work. The cavity design is illustrated in Figure 2 on page 10, and the specifications are given there and in Chapter II. The waveguide dimensions are d=.060", l =2", w=1.204", 2a=1.1", 2b=3.791", 2a=1.4", 2b=3.880", h=.7", and 2a"=2.6". The cavity is pictured in Figure 4. The discs were machined to have shoulders so that each disc would interlock with the circular waveguide section on either side of it. This allowed easy assembly of the apparatus and the flexibility to change the over-all length of the cavity by removing sections of the disc-loaded portion. Three rods external to the cavity were bolted at the end plates to insure firm contact of all brass pieces. The rectangular waveguides at the input and output ends were soldered to the 4 1/8 inch circular waveguide sections. The excess solder was then milled out so that the dimension d was again .060 inches. Care was taken in the machining and

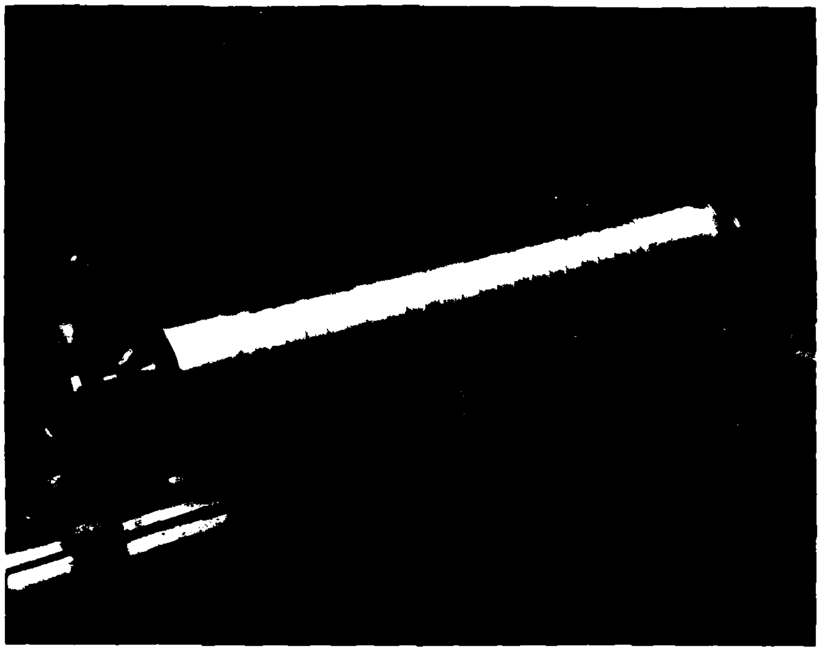

Figure 4. Brass Disc-Loaded Cavity

handling of the brass to prevent scratches, gouges, and other imperfections. However, the brass surfaces could not be totally protected. The cavity was dipped in a degreasing solution to provide a clean inner surface. The transformer discs were also constructed with shoulders so that from the input 4 1/8 inch circular section to the output one, all the brass pieces fitted together snugly. Eighteen disc-loaded sections were fabricated, giving the structure an active length of three feet.

The cylindrical stubs on either end of the cavity were designed to prevent leakage from the cavity while allowing the insertion of a plasma tube. The diameter of .75" for the stub cuts off microwave radiation at 2450MHz, since it is below the lowest circular waveguide diameter for propagation at that frequency. However, it was found during the experiment that a plasma in the cavity conducted power out the end (2mw of leakage was measured with a Microtek 310 leakage meter). Therefore, an aluminum foil cone was placed around the cavity ends to prevent any stray radiation. Three 1/4 inch diameter viewing ports to observe the plasma were drilled in the circular waveguide sections at the ends and in the middle of the cavity. There was no detectable leakage from these ports or anywhere else in the structure.

The microwave cavity was supported on an optical bench by 3 y mounts that were fabricated specifically to match the curvature of the cavity. The remaining microwave components needed to operate and characterize the structure were then connected at either end of the cavity. The experimental arrangement is shown in Figure 5 and Figure 6 gives a schematic for the set-up.

Three different sources were used to supply microwave power to the system. A Hewlett Packard (HP) 8620 C sweep oscillator was used in the characterization studies of the cavity; a Raytheon model PGM-10 was used to supply CW power to the system; and a Peschel Instrument Inc. 500W magnetron was used to supply higher CW power. The isolator was an Airtron model IL-241F PS-14 and the waveguide to coaxial adapters were all HP's. The 10 decibel (db) directional

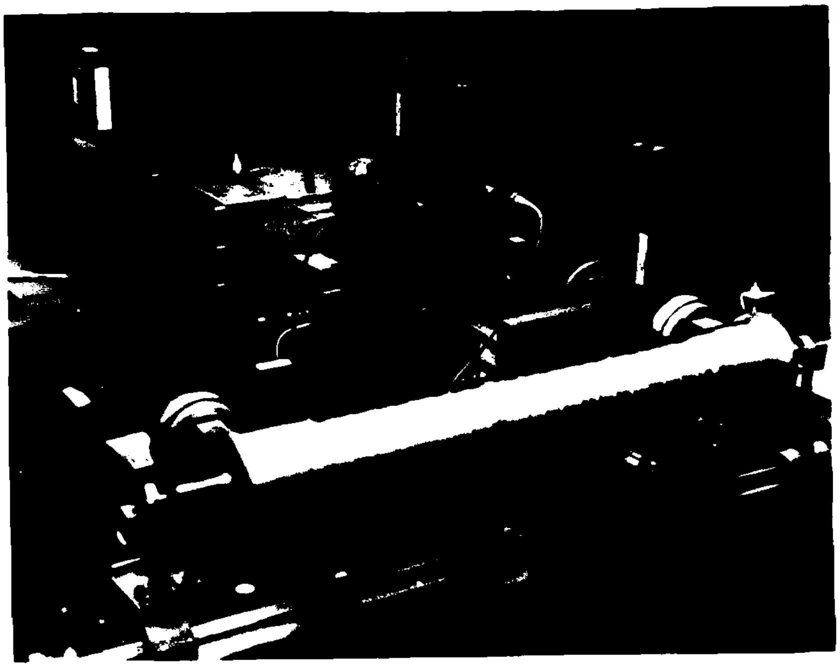

Figure 5. Experimental Arrangement of Microwave Components

coupler was a HP model 87620 and the 3db coupler an HP S752A. The attenuators indicated are combinations of Narda 20 db couplers with various Weinschel Engineering coaxial attenuators. The small loads were Microwave lab 10 watt loads. The large load was a HP model S912-A. The input and transmitted power meters were HP 432B meters with Struther's model G/L-360 detector mounts. A Boonton Electronics model 42-A power meter with 41-4B detector mount was used to measure the reflected power. The circulator was a Merrimac FCW-584 and the E/H tuner was a FXR S312A. The slotted line was a HP S-810A and a PRD 250A probe was used in it. This probe, with a IN21C diode, was connected to a PRD 277-D

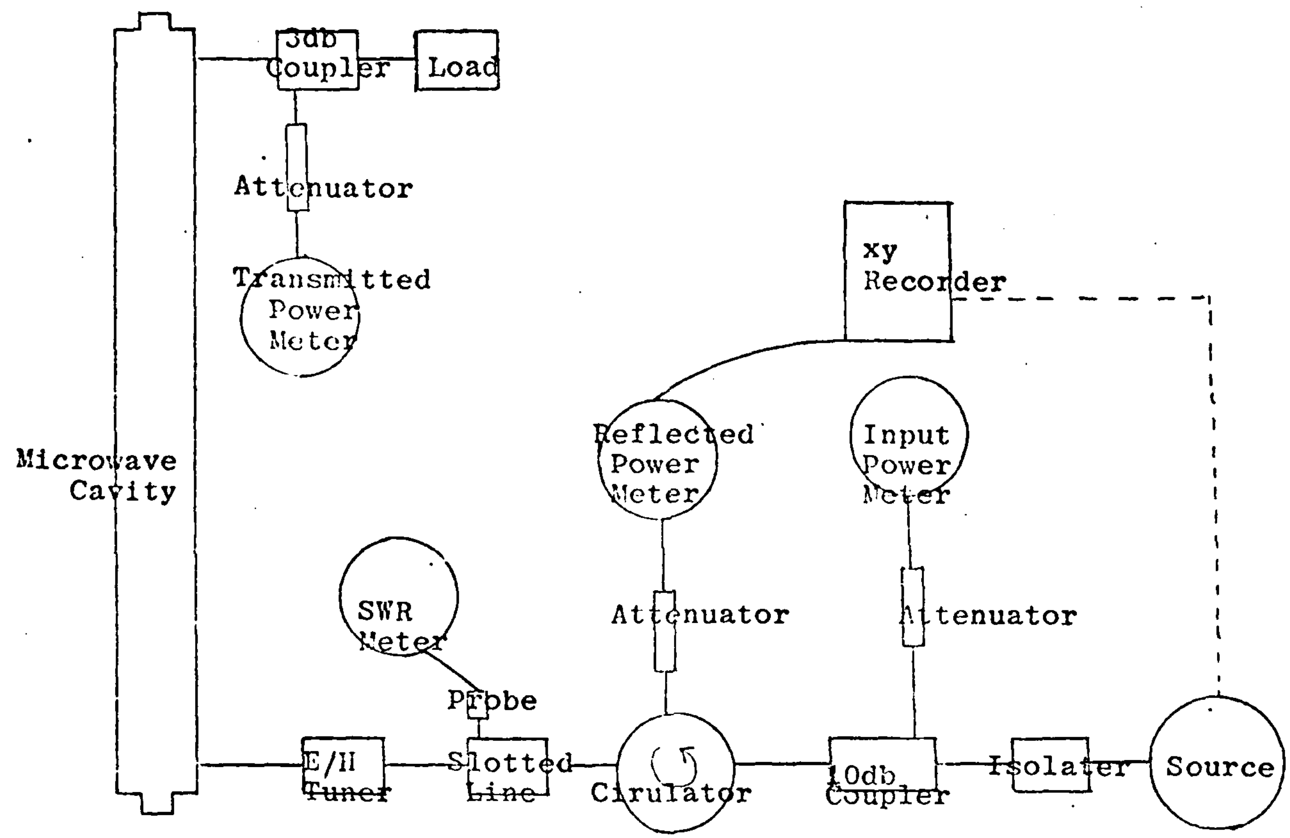

Figure 6. Schematic for Microwave Cavity and Associated Microwave Components.

SWR/attenuation meter. Finally, an Electro Instruments X-Y recorder model 400, was used to observe the reflected power.

When the Peschel magnetron was used, it became necessary to modify the arrangement of Figure 6 because of the higher power levels. The 10db coupler was replaced by a HP S750D 20db directional coupler and a Raytheon CSH148 circulator was used instead of the Merrimac due to its higher power rating. The coaxial attenuators could not be used either, and a rectangular waveguide section with a small loop in it was used to sample the reflected power. The loop coupling factor was experimentally determined, and was found to vary with input power. Therefore, the reflected power found using it could not be guaranteed and was only used to determine trends in the reflected power. The waveguide with the loop was terminated by a Raytheon LSH 102 load. On the transmitted side of the cavity, the 3db coupler was replaced by the 10 db coupler that had been on the other side. This still required particular attention in operation because the transmitted power circuit could not handle the full power of the magnetron. Therefore, the discharge was always well-established and absorbing a large portion of the power before the higher power levels were selected.

A final configuration of the system involved using both the Raytheon and Peschel generators to supply CW power. The Peschel generator input side remained unchanged from the previous set-up. On the other side of the cavity, the 10db coupler was disconnected and its direction was reversed. The input side of the coupler was then connected to the Raytheon generator. On the output side of the coupler, a Raytheon circulator was used to direct the reflected power (and the transmitted power from the other side) into a HP 100W load. Another calibrated loop in a short waveguide section before the load was used in measuring this power. A FXR E/H tuner between the circulator and the microwave cavity completed the circuit.

One additional microwave circuit was used at times. A FXR N410A frequency meter replaced the load in the reflected power circuit in Figure 6 and was connected to a HP 120 B oscilloscope. The microwave source also supplied a signal to the oscilloscope and this provided a means to measure the frequency of the source.

LASER APPLICATION COMPONENTS

The laser application components consist of a vacuum manifold and associated equipment, the discharge tube, and the required optics for completing the system and making measurments. An over-all view is given in Figure 7. A Welch Scientific turbopump was used. The manifold was configured so that six different gases could be used in the system. A Granville Phillips ionization gauge with a Fluke 8300 A digital volt meter was used to measure the low pressures down to 10^{-9} torr.

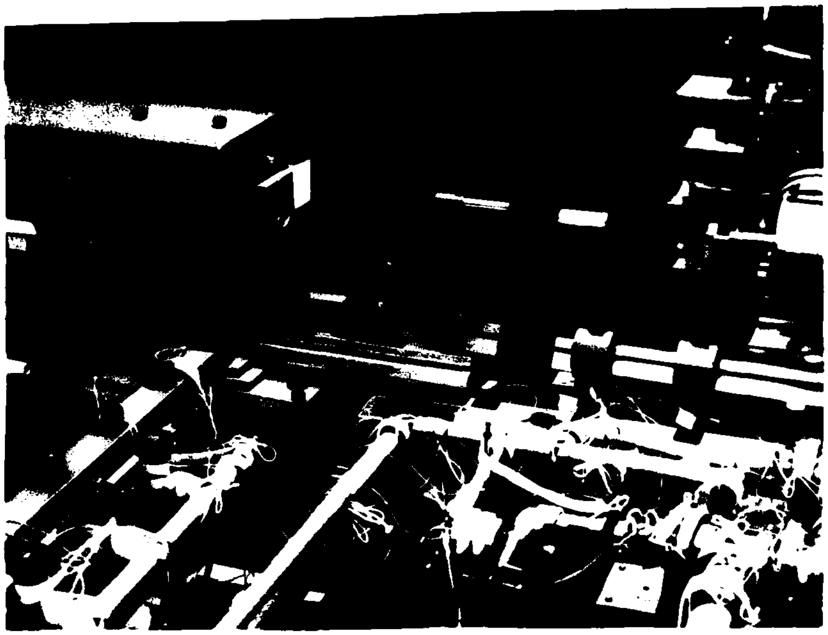

Figure 7. Experimental Arrangement of Optics and Vacuum System

The discharge tubes were made of quartz to handle the microwave heating. Quartz windows were epoxyed to either end and the tube was connected to the rest of the system using a T-section. Leak checks of the system were performed with a Tesla coil.

Two laser tubes were also constructed with inside diameters of 1.83mm and 3.5mm. The 1.83mm tube was a capillary. Bell flares were made at each end of the laser tubes and these flares were ground to a Brewster's angle of $55\frac{1}{2}^{\circ}$. Once the tubes were inserted in the microwave cavity, Lambda/Airtron 13mm elliptical Brewster windows were epoxyed on. Broad band mirrors with reflectivities of 99.9% were then put on Lansing Research Corp mounts to complete the laser system.

A model 82020 Jarrell Ash spectrometer with collimating optics was used to measure the emission spectra of the microwave discharges. An EMI 9558QB photomultiplier was powered by a Power Designs high voltage source at 1680V, and was placed at the exit slit of the spectrometer. The photomultiplier signal was sent through a 10K load resistor and then to a Varian G-2000 recorder.

IV EXPERIMENTAL PROCEDURE

INTRODUCTION

This section describes the procedures used in this investigation. First, the method utilized to characterize the microwave cavity will be detailed. Then the procedures used to determine the best conditions for an excited plasma in the cavity will be outlined. The parameters that were varied included the input microwave power, the pressure of the laser gases in the plasma tube, and the bore of the plasma tube. Finally, the methods used to investigate the laser properties of the system will be specified.

CHARACTERIZATION OF THE CAVITY

The microwave cavity described in the previous section first had to be characterized. The dimensions h and 2a" needed to produce the best impedance match in the transformer had to be determined expermentally. The passband for the structure also had to be determined, and the voltage standing wave ratio (VSWR) had to be measured. All of these tasks were accomplished with the set-up illustrated in Figure 6 on page 22. Actually, various geometries with different dimensions h and 2a" were tested.

One of these configurations was assembled and the cavity was connected to the rest of the system. The HP sweep oscillator supplied the input signal, and its frequency tuning was calibrated with the FXR frequency meter and the oscilloscope. However, this equipment had an error of ±1 MHz and the frequency also varied with temperature, which could not be controlled in the laboratory. It was found that the VSWR of the structure varies rapidly with frequency, and, therefore, the inability to precisely control the frequency input meant that VSWR measurements could not be reproduced exactly. Stopbands and passbands could still be determined.

The VSWR was measured for each configuration at various frequencies in the range from 2420 MHz to 2480 MHz. The slotted line, probe, and SWR meter were used for this, and consistent results were obtained with the above noted exception. A plot of VSWR versus frequency was then made for the structure to determine its impedance match.

The variation of reflected power with frequency also gives a good indication of a structure's impedance match. Therefore, the reflected power measured at the Boonton meter was inputted to the XY recorder, and the other input came from the sweep oscillator. The sweep oscillator was operated in the sweep mode, with a frequency sweep range of 200 MHz centered at 2450 MHz. The power spectrum obtained on the XY recorder could not be easily calibrated, but still gave a solid indication of the cavity's impedance match.

All of the above measurements were conducted with an empty cavity and with the E/H tuner set to have no effect. It was desired to see what effect a plasma in the cavity might have on the system. To simulate a plasma, an aluminum rod was placed in a quartz tube and this system was inserted down the center of the cavity. This was the worst possible case for a plasma, and the VSWR and power spectrum measurements were then repeated.

The E/H tuner was utilized to determine the minimum VSWR which could be obtained. This was performed at various frequencies for an empty cavity and for one loaded with an aluminum rod and quartz tube. The final choice for the cavity geometry was then made, and attention was then focused on determining the optimum conditions for an excited plasma in the structure.

OPTIMIZATION OF THE PLASMA DISCHARGE

With an appropriate cavity, the other parameters of the system, including the input microwave power, the gas pressure, and the bore of the plasma tube, could be optimized for laser applications. Three tubes of inside diameter 8mm, 3.5mm, and 1.8 mm were used and plasmas generated in helium and argon gas were studied. The gas pressure was varied continuously down to hundreths of a torr with the vacuum system and the Raytheon microwave generator supplied up to 90 watts of input power. The spectrometer was used to obtain the spontaneous emission spectra in the plasma tube.

A completed tube was inserted down the length of the microwave cavity and supported at either end on the optical bench exterior to the cavity. The final connection was made to the vacuum system in place, and the tube was pumped down and degassed. A vacuum of at least 9 X 10^{-9} torr was obtained in each case. Microwave power was then supplied to the system, and the input, reflected, and transmitted powers were measured. In this way, the losses of the cavity could be determined.

The gas (argon or helium) was then fed into the plasma tube. At various pressures and input power levels, the resultant discharge in the tube was observed and studied. The input, reflected, and transmitted powers were continuously monitored, and E/H tuning was used to minimize the reflected power. Initially, the Raytheon generator was used as the power source, and when higher power levels seemed to be warranted, the Peschel unit was employed. A final configuration utilized both generators and power was supplied to both ends of the cavity.

SPECTROSCOPIC MEASUREMENTS

With a discharge in the tube, an attempt was made to obtain lasing. However, it was first desired to perform a spectral analysis of the microwave discharge. This was accomplished for argon using the spectrometer and associated components described in Chapter III. The system was calibrated with a mercury lamp. A spectrogram for argon was obtained and analysed for known laser transitions. This analysis was performed to estimate the probability that the system would lase.

The laser tube was then aligned using a white light source and a beam splitter. The alignment was checked with a small He-Ne laser. The 1.8 mm tube could not be adequately aligned due to sag caused by its own weight and imperfections in the bore. Sag was also a problem with the 3.5 mm tube, and a non-conducting hook was therefore placed through the middle viewing port to support the laser tube. The system was then aligned, and lasing was attempted with argon. Power was supplied to each end of the microwave cavity, and various pressures of the gases were used.

V RESULTS AND DISCUSSION

The experimental results will be given and discussed in this section. The major problems encountered in this study will also be analysed. First, the results of the microwave cavity characterization experiments will be given. Then the plasma optimization studies will be summarized and analysed. Finally, the laser properties of the system that were observed will be discussed.

PROPERTIES OF THE MICROWAVE CAVITY

The VSWR and reflected power spectrum measurements performed on various geometries of the microwave cavity revealed that the transformer dimensions h=.7" and 2a"=2.6" produced the best impedance match. The VSWR measurements for this final configuration are shown in Figure 8. This graph compares favorably with the input VSWR that Van Koughnett *et.al*. measured for their structure (Ref 6:202). A plot for a non-optimum structure (h=.8", 2a"=2.4") is shown in Figure 9 for comparison. The passbands for the two structures are similar, but the first structure has a consistently lower VSWR in the tested frequency range. The structure of Figure 8 was therefore determined to be the most suitable for the present application. This optimization was further aided by noting the effect of E/H tuning on the VSWR values. At any

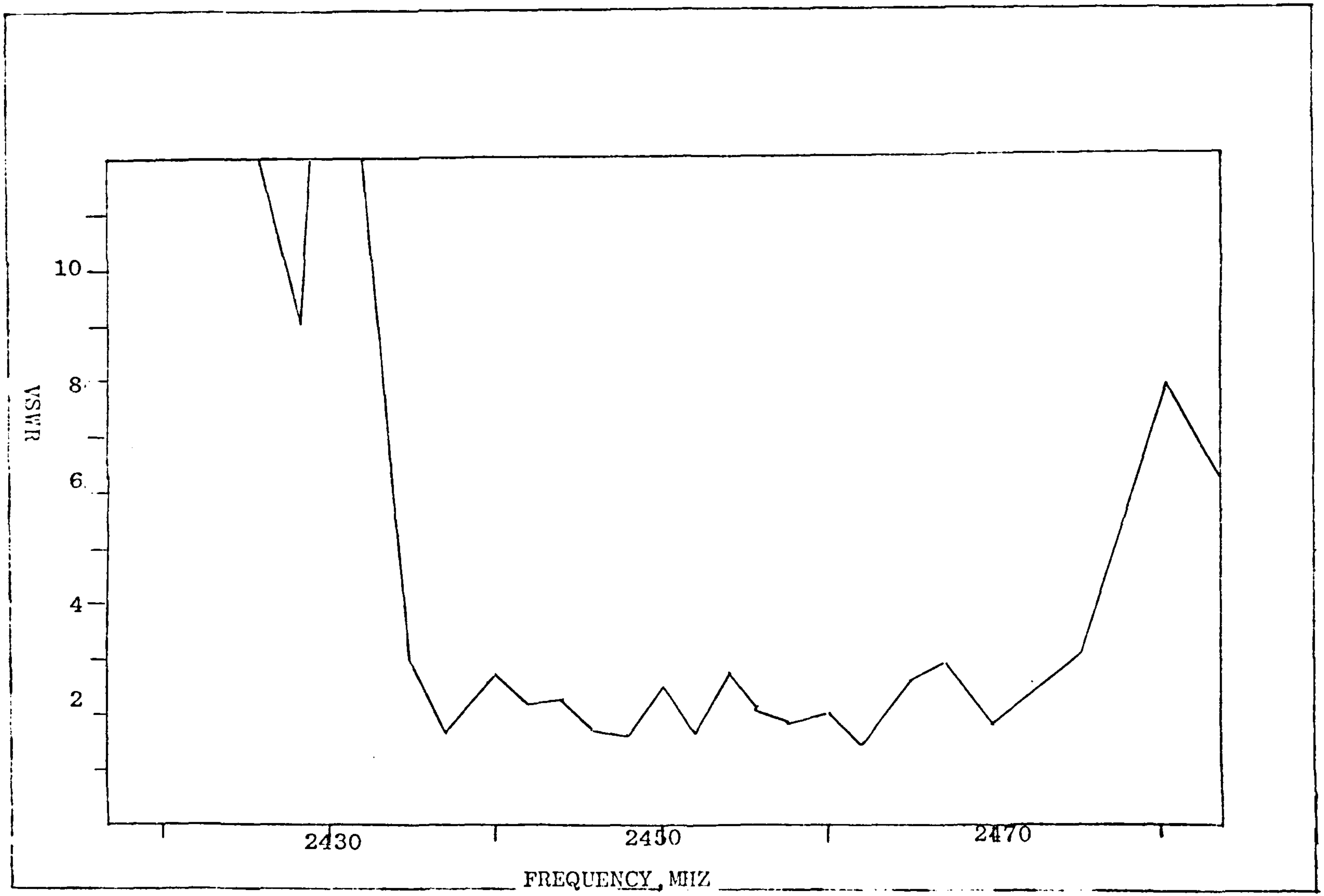

Figure 8. VSWR of The Disc-Loaded Cavity vs. Frequency For The Optimum Geometry.

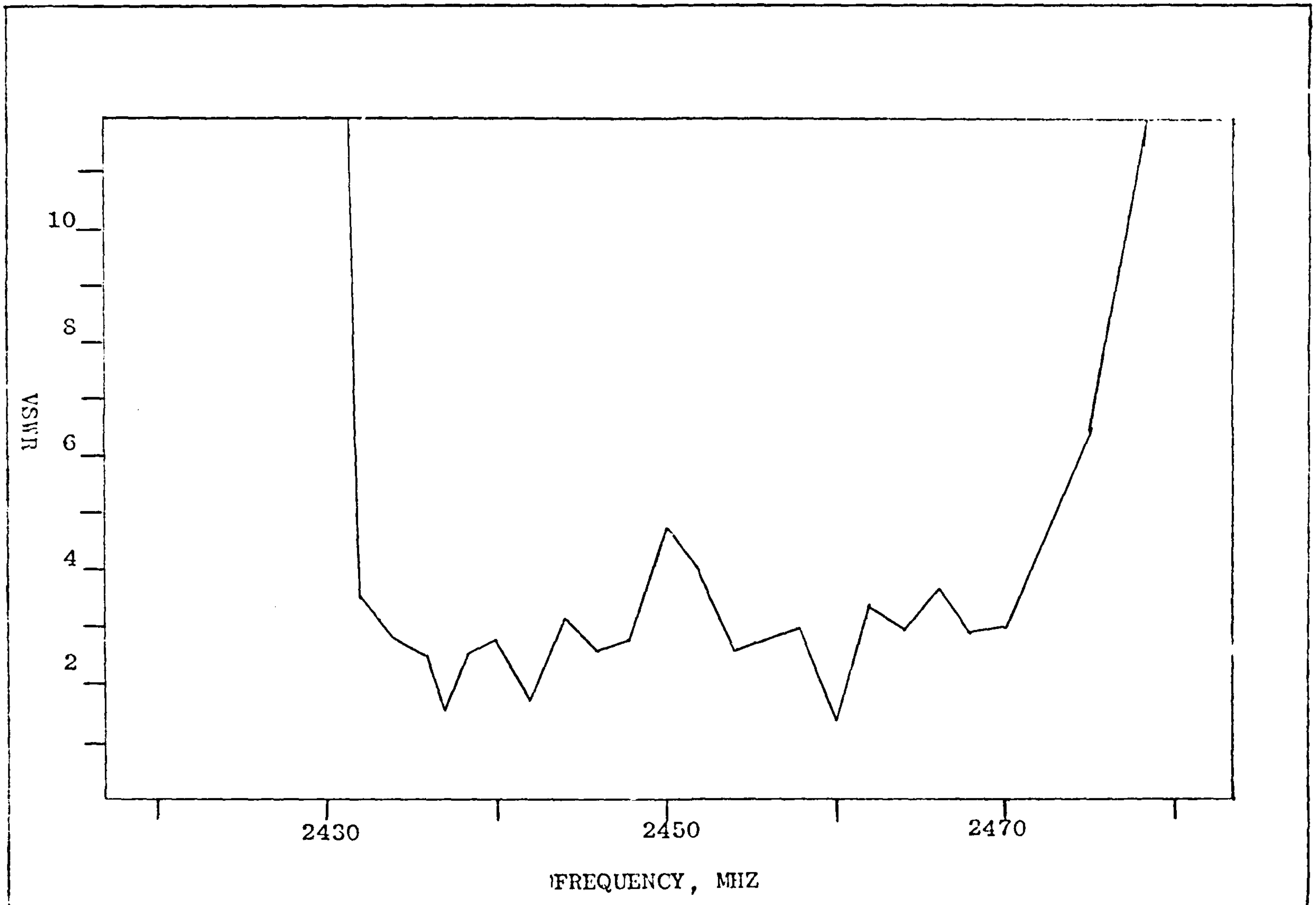

Figure 9. VSWR of The Disc-Loaded Cavity vs. Frequency For A Non-Optimum Geometry.

frequency in the passband, E/H tuning could be used to drive the VSWR below 1.5.

The final reflected power spectra which were obtained for the structure are shown in Figure 10. The solid line in the graph is for an empty cavity; the dashed line is for a cavity loaded with an aluminum rod in a quartz tube. The passband for the structure is readily seen and confirms the VSWR measurements. The spectra for a non-optimum geometry are shown in Figure 11. Although the power units are arbitrary, the same scaling was used for both plots. Clearly, the reflected power does not drop as much in the passband for the non-optimum case as it does for the optimum configuration. The power spectrum for the loaded cavity in the optimum case causes a considerable problem. Since the rod simulates a plasma, the plot indicates that at certain frequencies, a highly conductive plasma creates a considerable impedance mismatch. The VSWR of the loaded cavity was also measured at certain frequencies, and was always higher than the VSWR for the unloaded cavity at the same frequency. It was not possible to reduce the VSWR below 4.0 with E/H tuning at several frequencies in the passband. However, since the cavity loaded with a metal rod represents the most conductive plasma possible, it was felt that the high VSWR values would not be the over-riding factor in the usage of the cavity with an actual plasma, which would have a lower conductivity.

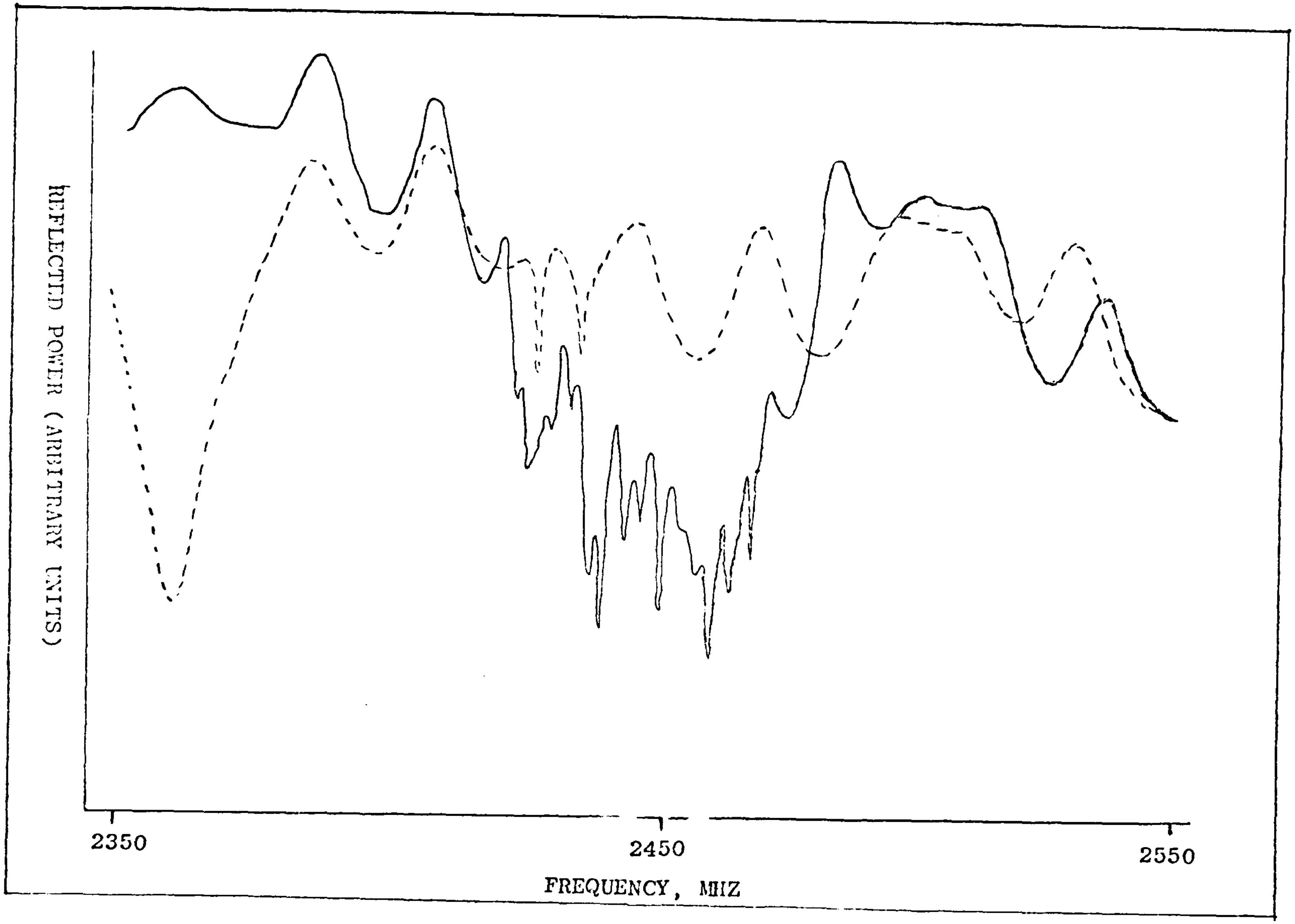

Figure 10. Reflected Power vs. Frequency for Optimum Geometry.

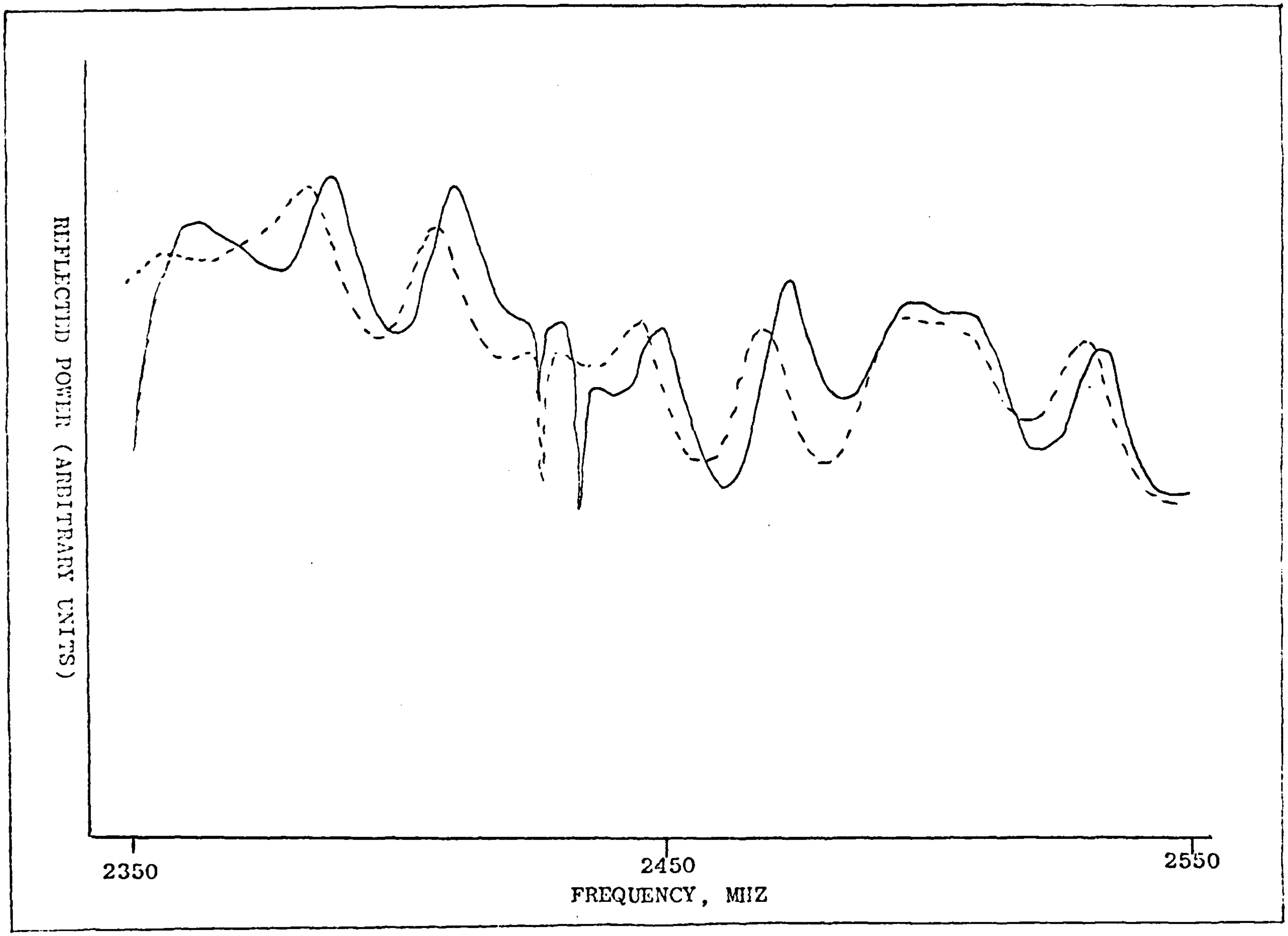

Figure 11. Reflected Power vs Frequency For A Non-Optimum Geometry

The insertion loss was the final important property of the microwave cavity that was determined. It was measured at 10 different power inputs and the mean value obtained was 6.3db. This was very much higher than the value of 1.7db that Van Koughnett _et_. _al_. obtained for their cavity, and is definitely undesirable. However, this high value was not totally unexpected since the brass surfaces of the microwave cavity were not optimum. Machining and handling of the brass pieces caused a considerable number of small imperfections in the waveguide interior. Electro-polishing or silver plating would have undoubtedly improved the insertion loss, but were not available options in this experiment. During system operation, the high insertion loss of the cavity was evidenced by a marked increase in the temperature of the waveguide itself. The high losses of the cavity also required a larger power input than originally planned to excite the plasma and necessitated the use of the larger generator.

PARAMETERS FOR THE PLASMA DISCHARGE

The microwave power, bore diameter of the plasma tube and gas pressure were all critical to system operation. The amount of microwave power that could be coupled to the plasma proved to be the determining factor in the establishment of a uniform microwave discharge. The problems of high reflected power caused by the impedance mismatch of the plasma and the large insertion loss of the cavity necessitated power levels much higher than originally anticipated. It was not possible to establish a uniform discharge the whole length of the cavity with just 90w of input power from the Raytheon generator. When the Peschel unit alone supplied input power of 200-300W, the plasma discharge established in the input end of the cavity became much more intense, but still did not extend the whole length of the cavity.

The E/H tuner was used to maximize the length of the discharge, but it was concluded that a uniform discharge could not be obtained when the power was fed to the system from just one end. Therefore, the set-up was changed so that power could be supplied to both ends of the cavity. Again, the impedance match was critical, and E/H tuners were used on both sides of the cavity. The discharge was generally unstable (the active plasma would jump from one section of the tube to another and go out altogether at times), but simultaneous adjustments of the E/H tuners yielded an active plasma for the whole length of the cavity. It was also found that the establishment of the discharge was not solely dependent on the amount of power. The ratio of the input powers also affected the system. When the powers were approximately matched (within 10-20w), the discharge could be established. However, when the Peschel generator supplied significantly more power than the Raytheon, the discharge over the entire length could not be established. Increasing the power level of the Peschel would instead just increase the intensity of the discharge in one portion of the microwave cavity. Therefore, system operation was limited by the low power output of the Raytheon generator.

The bore diameter of the plasma tube was the second parameter that was investigated. It was desired to have as large a volume as possible, so the 8mm inside diameter tube was tested first. However, the large reflection and power constraints quickly precluded the use of the 8mm tube, as a discharge could only be established in approximately 1/3 of the length of the tube. Preliminary investigations showed that the VSWR of a loaded cavity decreased monotonically with the bore diameter of the quartz tube (which always contained a tight-fitting rod). Therefore, only 3.5mm and 1.8mm tubes were investigated further. Uniform discharges in argon and helium-neon were obtained in both tubes with approximately 180W of input power from the generators.

The pressure of the laser gases was the last parameter that was investigated. Various pressures in the range of .2 torr to 10 torr were tried in intervals of .25 torr. Discharges were established at several different pressures, but the final configurations had pressures of .50 torr for argon and 1.75 torr for helium-neon (87.5% helium,12.5% neon) in the 3.5mm tube.

LASER PROPERTIES OF THE SYSTEM

The feasibility of using the disc-loaded microwave cavity as the pump for certain gaseous lasers was demonstrated in this experiment. The spectrogram obtained for an argon discharge in the structure is shown in Figure 12. An analysis of this spectrogram quickly shows the system's capability to produce lasing action. The laser transitions for the argon II ion observed previously (Ref 20:73) are annotated on the diagram. The other strong lines on the spectrogram are argon neutral lines which will not be discussed here. The relative intensities of the laser lines are in good agreement with the results of Paik and Creedon, who studied an argon ion microwave discharge that utilized a different cavity geometry (Ref 21:2086-87). The 4880 Å laser line, which is produced by the transition $4p^2_{3/2}D \rightarrow 4s^2P_{1/2}$, is the strongest laser transition found in Figure 12, and it was also observed that as the input microwave power was increased, the intensity of the 4880 Å line also increased.

These results clearly indicate that an argon ion laser operated at 4880 Å would be feasible using microwaves in the disc-loaded cavity as the excitation mechanism. A laser cavity was formed, using the 3.5mm discharge tube filled with argon at a pressure of .50 torr. The input power from the generators was varied from 180W to 450W. An intense spot of stimulated emission, known as a "fireball," was observed

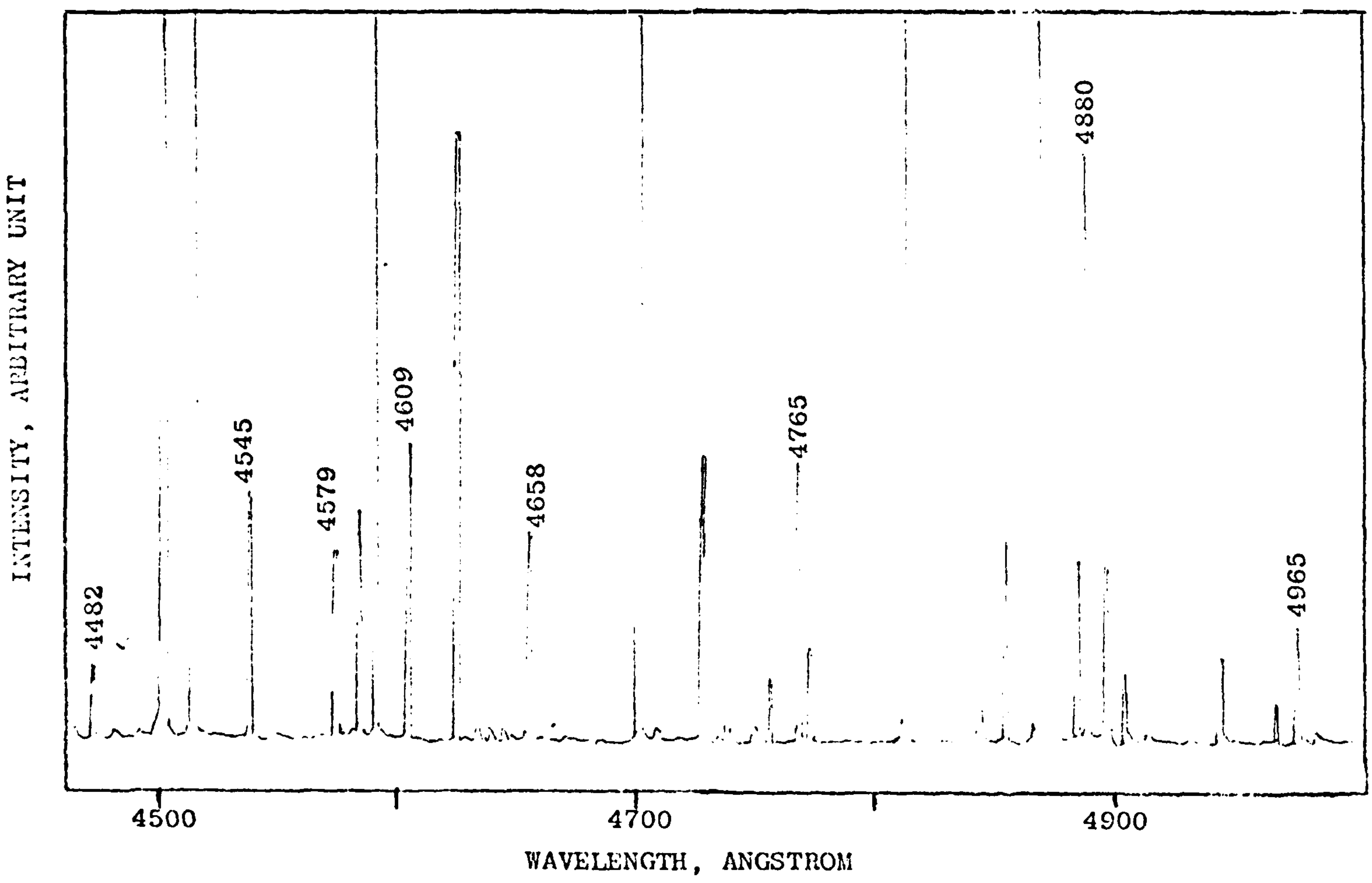

Figure 12. Spectrogram for Argon Discharge. Labelled Spectral Lines Are Known Argon Ion Laser Transitions.

in the discharge and indicated that the system was just below the threshold for lasing. However, attempts to optimize the system to achieve lasing were not completed.

VI CONCLUSIONS

This study has shown the feasibility of using the constructed disc-loaded microwave cavity as the pump for gaseous lasers. A uniform argon discharge was obtained in the cavity, and known argon ion laser transition lines were observed when a spectral analysis was performed. Attempts to optimize the system configuration for lasing were not completed, but it is felt that additional work and equipment changes would readily lead to lasing.

The disc-loaded cavity was first characterized by measuring its VSWR and insertion loss. The VSWR for an empty cavity was found to be 1.5 or lower for any frequency from 2425 MHz to 2475 MHz. With a metal rod in a quartz tube inserted in the cavity to simulate a plasma, the VSWR increased to values as high as 4.0 in the same frequency band. This effect also occurred with an actual plasma. The insertion loss of the cavity was measured to be 6.3 db. It was discovered that this loss adversely affected the amount of power that could be coupled to the plasma. A major factor in the cavity's high insertion loss was the imperfect inner brass surfaces. A substantial improvement could be obtained if the inner surfaces of the brass components were electro-polished or silver-plated. Soldering the components together instead of press fitting them together would also reduce the insertion loss. It would be absolutely essential to improve on the insertion loss in order to achieve efficient lasing action.

A uniform microwave discharge with argon and with helium-neon was obtained in the disc-loaded cavity. The argon discharge was established at .5 torr in the 3.5mm tube with 180W of input power. The He-Ne discharge was produced under similar conditions except for the gas pressure which was 1.75 torr. In both cases, the establishment of a uniform discharge depended heavily on E/H tuning and on coupling of the power to the plasma. It was determined that the power inputs to the two ends of the cavity also had to be approximately matched in order to establish a uniform discharge. A larger power supply with a splitter could be used in future work to insure the matching of the power inputs and greater power coupling to the plasma. Uniform discharges could also be obtained more easily by reducing the plasma volume. This could be accomplished by removing sections of the disc-loaded cavity, or by decreasing the plasma tube bore diameter. This alternative is not as attractive as changing the power supply, since it will usually be desired to maximize the plasma volume.

A spontaneous emission spectrogram for the argon discharge was obtained and analysed. Known laser transitions were identified, and the 4880 Å line was the most intense. A "fireball" was also observed in the discharge when a laser cavity was formed. These results demonstrate the feasibility of laser action in the disc-loaded structure. However, attempts to optimize the system configuration to obtain lasing were not completed.

In conclusion, this experiment has only touched on the preliminaries of utilizing a disc-loaded microwave cavity for laser applications. The feasibility of laser action was demonstrated, and further work is warranted. Changes in the experimental apparatus and the cavity itself would facilitate this work, and will be detailed in the next section. Still, the disc-loaded microwave cavity definitely holds promise for future laser applications.

VII RECOMMENDATIONS

The excitation of lasers with microwaves has definite advantages over other excitation mechanisms, and should be explored further. The disc-loaded microwave cavity system used here can be improved upon significantly, and, therefore, should also be investigated further. The results of this experiment indicate that changes in the experimental apparatus and the cavity itself should result in lasing for an argon ion system. These changes include: (1) driving the source magnetron only at the particular frequency that yields the lowest VSWR for a loaded cavity; (2) electro-polishing or silver-plating the brass components of the cavity to reduce its insertion loss; and, (3) using a larger power supply with a splitter in order to couple more power to the plasma. Once lasing is obtained, the efficiency of the system should be measured, and a spectral analysis of the laser beam should be performed. These results should then be compared and contrasted with similar results from other argon lasers that use different excitation mechanisms. In this way, the desirability of employing microwave excitation could be determined for an argon ion laser.

The disc-loaded microwave cavity system should also be investigated for use in other types of laser systems. Metal vapor and metal halide lasers are possibilities, and only minor modifications would be required to the present apparatus. A significant advantage of employing microwave excitation with these systems is that the microwaves could possibly be used to vaporize the metal, and an external heating mechanism would not be required.

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A brass disc-loaded microwave cavity was built and the feasibility of using it as the pump for an argon ion laser was investigated. The cavity was 3 feet long and its insertion loss was measured to be 6.3 db. The voltage standing wave ratio for an empty cavity was found to be below 1.5 at all frequencies from 2425 MHz to 2475 MHz. A quartz laser tube was inserted in the microwave cavity and filled with .50 torr of argon. A uniform discharge was obtained with 180 W of input power, and a spectral analysis revealed that

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BLOCK 20: Abstract (Cont'd)

previously known laser transitions occurred in the discharge. A laser cavity was formed, and a "fireball" was observed in the discharge. However, attempts to optimize the system to obtain lasing were not completed. It was concluded that improvements must be made to the cavity to decrease the insertion loss and to the power supply to more effectively couple power to the plasma.

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