DOE/R3/40445--T1

Electrodeless Lighting
RF Power Source Development

Final Report

August 30, 1996

National Industrial Competitiveness through
Environment, Energy and Economics
NICE^3

Prepared Under Agreement GR 95-001-915-000
for
Maryland Energy Administration

for
US Department of Energy
Contract Number DE - FG 43 - 94R 340445

Prepared by
Northrop Grumman Corporation
Electronic Sensors and Systems Division
Baltimore, Md. 21203

DISCLAIMER

DISCLAIMER

Electrodeless Lighting
RF Power Source Development

Final Report

August 30, 1996

National Industrial Competitiveness through Environment, Energy and Economics
NICE^3

Prepared Under Agreement GR 95-001-915-000
for
Maryland Energy Administration

for
US Department of Energy
Contract Number DE - FG 43 - 94R 340445

Prepared by
Northrop Grumman Corporation
Electronic Sensors and Systems Division
Baltimore, Md. 21203

ELECTRODELESS LIGHTING
RF POWER SOURCE DEVELOPMENT

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SUMMARY

The goals of the National Industrial Competitiveness Through Environment, Energy, and Economics ($NICE^3$) programs are to improve energy efficiency, promote cleaner production and improve competitiveness in U. S. industry. The DOE and EPA sponsor projects to achieve these goals. Such projects focus on the demonstration, deployment and dissemination of energy efficient and environmentally cleaner production technologies. The targeted technologies should be transferable to a wide range of applications and should advance the state of the art by overcoming restraints that currently limit energy efficiency and cleaner production.

The specific goal of this $NICE^3$ project was to develop an efficient solid state RF power source which takes full advantage of concurrent advances in electrodeless lamp technology which offer significant energy savings and a reduction in the generation of toxic wastes compared with conventional incandescent and florescent lighting systems. To accomplish this goal, Northrop Grumman Corporation and Fusion Lighting, Inc.,collaborated in the development of an RF source to energize an electrodeless lamp. Northrop Grumman has applied its expertise and experience in solid state RF power generation in radar and communications systems to conceive and develop an efficient, compatible RF circuit to drive the lamp. Fusion Lighting has supplied its lighting expertise, experience and its latest coupling device and electrodeless lamp designs.

This technology is indeed transferable to a broad range of applications such as lighting for offices, factories, transportation facilities (eg. airports, train and bus stations, parking lots, highways), maintenance facilities, and medical facilities just to name a few. The energy efficiency, long life, broad spectrum and low maintenance offer sufficient advantages to be attractive to a wide variety of potential users. Furthermore, no mercury (Hg) is utilized in the bulb which avoids the environmental and economic (disposal costs) concerns compared to lighting products which contain Hg.

An "Electrodeless Lighting System" is defined to include all hardware from the prime power source up to and including the electrodeless lamp. Therefore, the lighting system encompasses power conversion circuits, RF generation circuits, matching/coupling circuits and the lamp itself. Since the goal of this $NICE^3$ project was to develop an efficient solid state RF

source to support the new electrodeless lamp, this report concentrates on the RF source circuit design and test results. The RF source is defined to include all circuitry from the prime power input up to the coupling device. Several trade-offs and analyses considered in determining the RF source architecture are described and recommendations to increase the overall efficiency of the lighting system are presented.

The real significance of the success of this project is illustrated in the projected energy and waste savings which will result from applying this technology in the United States. Based upon 1990 data indicating that commercial indoor florescent and incandescent lamps consume approximately 47% of the energy used for U. S. lighting, it is estimated the new RF energized electrodeless lamp could save as much as 20% of the annual U. S. lighting energy.

1.0 INTRODUCTION

An efficient, solid state RF power source has been developed on this NICE[3] project for exciting low power electrodeless lamp bulbs. This project takes full advantage of concurrent advances in electrodeless lamp technology. Northrop Grumman Electronic Sensors and Systems Division (ESSD) and Fusion Lighting, Inc. joined forces to accomplish the goal of the development of an RF source to energize an electrodeless lamp.

Electrodeless lamp lighting systems utilizing the sulfur based[1] bulb type developed by Fusion Lighting, Inc., is an emerging technology which is based on generating light in a confined plasma created and sustained by RF excitation. The bulb for such a lamp is filled with a particular element and inert gas at low pressure when cold. RF power from the RF source creates a plasma within the bulb which reaches temperatures approaching those of high pressure discharge lamp plasmas. At these temperatures the plasma radiates substantial visible light with a spectrum similar to sunlight.

The electrodeless lamp system is defined as all hardware from the prime power source through the lamp output. The RF source consists of that portion of the system up through the output matching circuitry but does not include the bulb, coupling device to the bulb, or bulb shields or protective devices.

This NICE[3] program has produced an efficient RF source, constructed from commercially available components, which has been successfully demonstrated. The RF source design is based on available bulb characteristics and the requirements for lighting this bulb. It includes an internal frequency source, power amplifier, and bulb matching circuitry. The RF source uses silicon RF field effect transistors and efficiency with these transistors is better than 60% overall when driving an electrodeless bulb. The output power amplifier efficiency, when delivering in excess of 100W into an optimum resistive load, is better than 80%.

This report describes the RF source, the requirements imposed upon it by the bulb and coupling device, presents the rationale for its development, and summarizes test results. It

---

[1]A sulfur based bulb is defined as one containing elements from column VI A of the periodic table.

includes a discussion of the several trade-offs and analyses considered in determining the architecture of the RF source.

The RF source circuitry is enclosed in a convection cooled package which incorporates a finned heat sink as illustrated in **Figure 1-1.** The coupling coil and the test bulb being energized by the RF are connected to the RF source on one end of the assembly as seen in the right hand side of the photograph. **Figure 1-2** shows the printed wiring assembly which contains all of the electronic components of the oscillator driver and power amplifier. The matching circuit components are mounted in the housing.

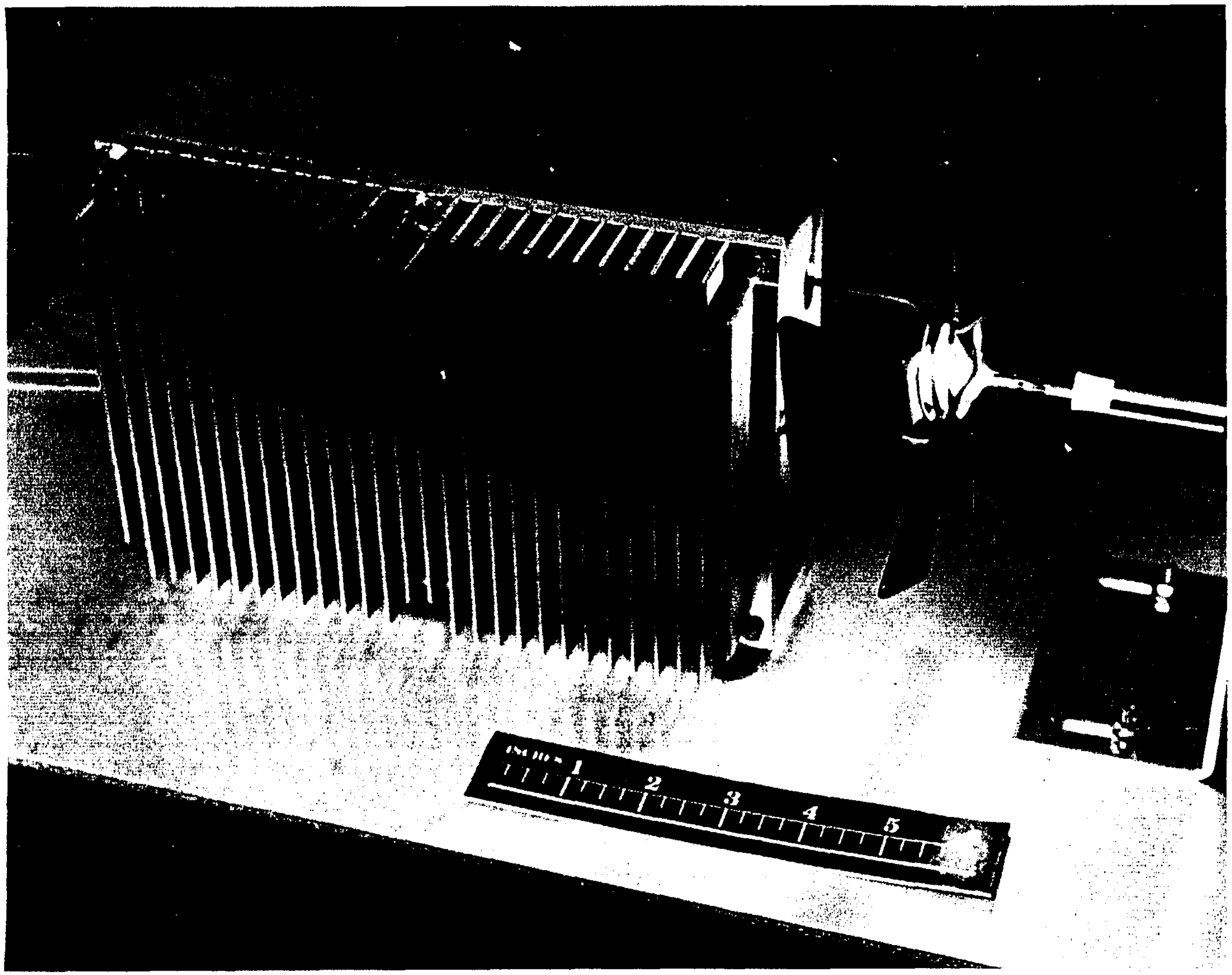


Figure 1-1. Power Amplifier and Bulb Energized

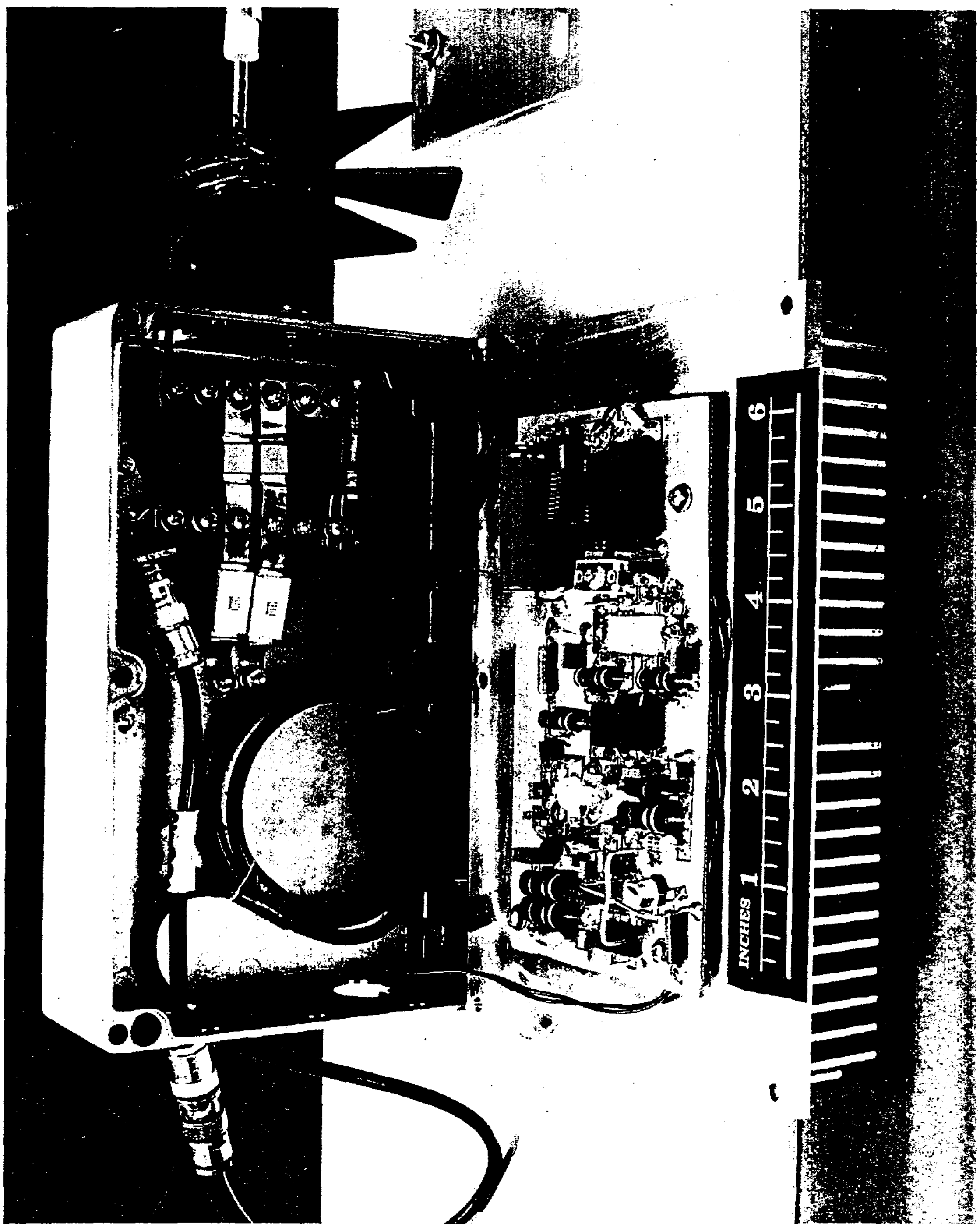


Figure 1-2. Inside View of RF Power Source

2.0 RF SOURCE SPECIFICATIONS AND LOAD CHARACTERISTICS

The RF source for the sulfur based electrodeless lamp consists of a solid state electronics circuit which converts power from its input format to that required to excite the bulb. RF source performance requirements and its load (coupling coil and bulb) characteristics are as listed in the following:

Power Input - The RF source draws power from standard commercial power distribution systems (120V, single phase).

Power Output - The power required by the bulb to produce optimum efficacy (light output / power in) is a function of bulb design. Based upon the projected bulb and coupler performance, the NICE^3 RF source is designed to deliver 110W of RF power to the coupling device under steady state bulb operation.

Operating Frequency - The operating frequency of the RF source is 27.00 MHz, a frequency within an ISM (Industrial, Scientific, and Medical) band. The frequency is generated within the RF source and all tuning reflects operation at this frequency.

Efficiency - The proposed goal of AC to RF efficiency (AC input to RF output to the coupling device) is 80%.

Cooling - The entire package is cooled by free convection from a finned surface.

Size - A size requirement would be established for the design of a specific lighting application. The overall dimensions of the RF source package as shown in **Figure 1-1** are 8.62" x 5.75" x 3.25". This includes an RF tight box, an attached heat sink, and sufficient space within the box to prevent excessive electromagnetic loading of the circuit by the box material.

Load Description - The RF source feeds a coupling device and sulfur based electrodeless bulb. Inductive coupling, employing a coil around the bulb, was selected as the coupling method to be employed for the RF source development.

Load Impedance - With inductive coupling, employing a coil around the bulb, the combined input of the coil and bulb is a complex impedance which is time varying. During steadystate, visible light emitting operation, the real impedance seen at the coupling device terminals is nominally one ohm resistive which is in series with 75 ohms of inductive reactance.

During bulb start-up, the input impedance to the coupling device varies in resistance and inductive reactance. This impedance variation results from the change in load from that initially presented by the coupling device itself (prior to bulb ignition) to the load eventually presented by the combination of the coupling device and the bulb when the bulb has reached steady state operation. The properties of the impedance of the coupling device and lamp reflected to the RF source are addressed in more detail in Appendix A.

3.0 CIRCUIT ARCHITECTURE

3.1 RF Source Topology

The RF Power Source consists of the four functional parts identified in **Figure 3-1.** The oscillator/driver is a crystal frequency source and buffer stage which supplies RF drive to the power amplifier of proper frequency and amplitude. The power amplifier amplifies the output of the oscillator/driver to a power level sufficient to drive the bulb to the desired brightness and efficacy of operation. The matching circuit tunes out reactance reflected from the coupling device and adjusts the impedance presented to the power amplifier such that amplifier current and voltage swings are within the limits of the amplifier component ratings.

The power supply converts commercial input power from AC to DC at an appropriate voltage. Because of voltage constraints imposed by the power amplifier transistor, an adjustable laboratory power supply was utilized during circuit development for this function. This function would be implemented by a simple bridge rectifier which rectifies directly from the power line without the necessity of voltage transformation. Higher voltage transistors available in the near future will make this circuit simplification possible.

3.2 Oscillator/Driver

Figure 3-2 is a schematic of the oscillator/driver portion of the RF source. The operating frequency of the RF Source is derived from a TTL level crystal oscillator. The entire crystal oscillator is in a DIP (Dual Inline Package) chip. It was designed to be used in personal computers and operates at 5 VDC and is inexpensive. For our demonstration power source, the required 5 volts was derived from the 30 volt supply via a Zener diode. Another Zener supplies a regulated voltage to the gates of the final power amplifier to maintain constant gain. A buffer stage and a driver stage between the oscillator and power amplifier isolates the oscillator from the power amplifier and provides the required power amplifier drive power level.

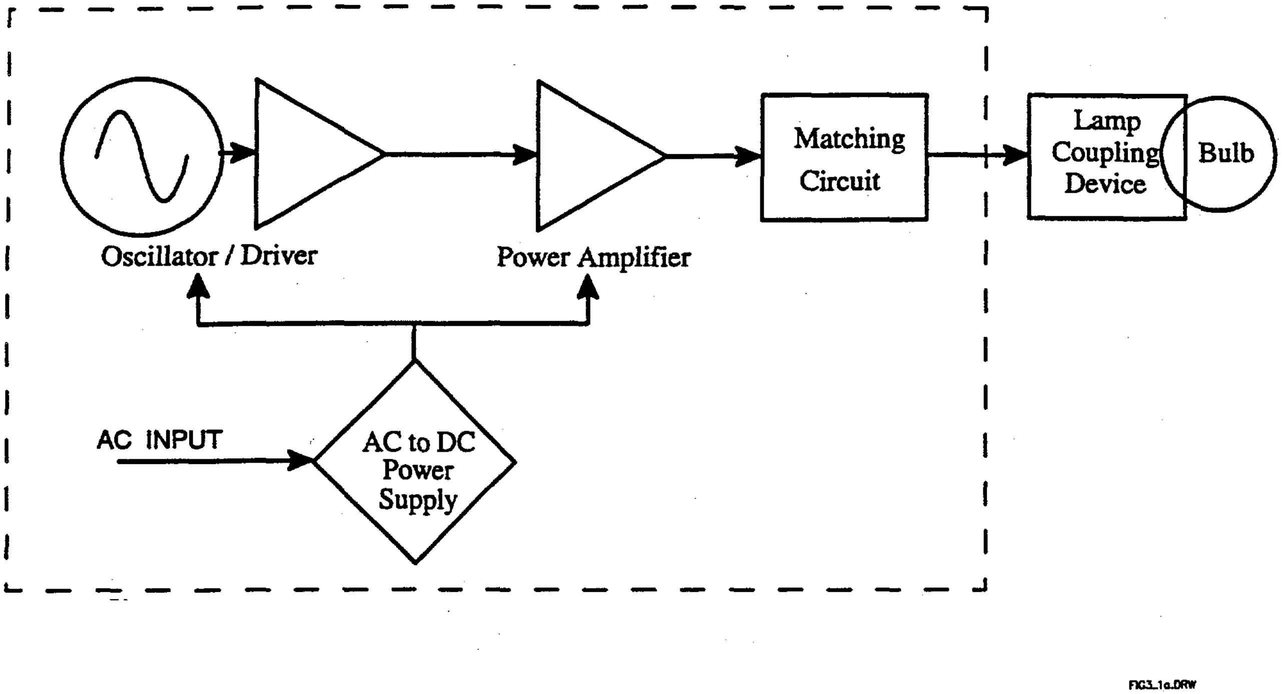


Figure 3.1. RF Power Source Functional Diagram

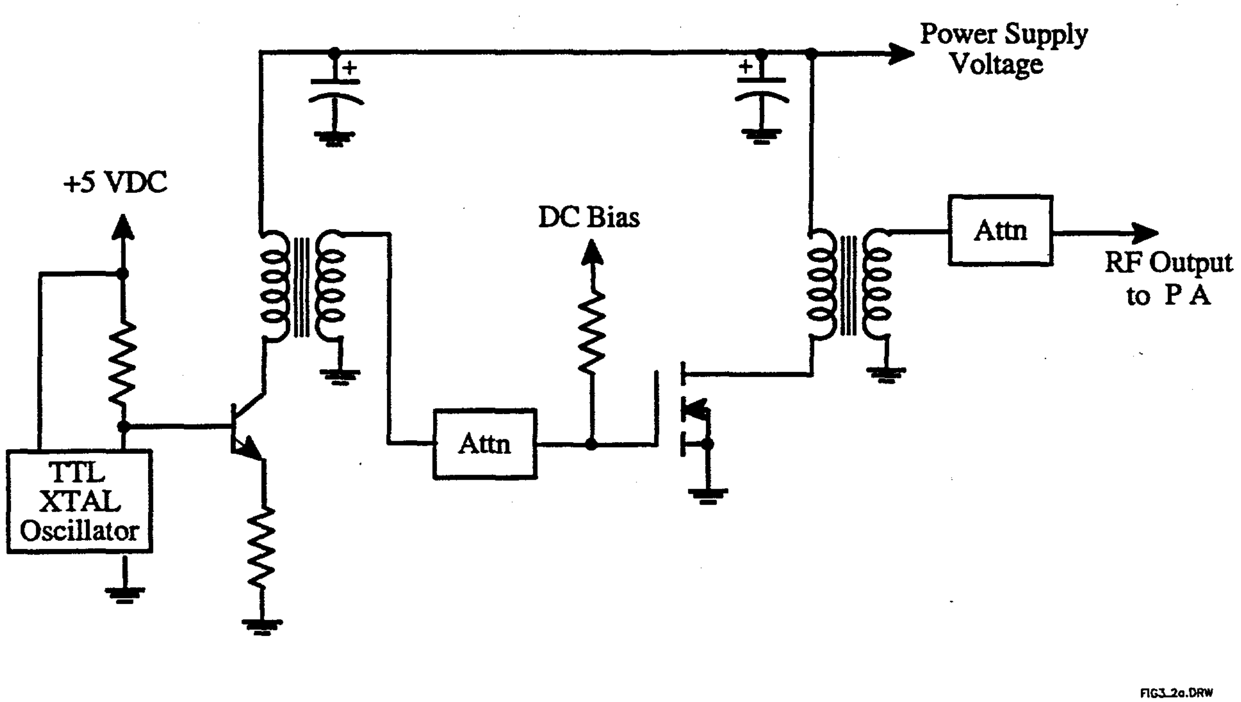


Figure 3.2. Oscillator and Driver Circuit

3.3 RF Power Amplifier

3.3.1 Power Amplifier Trade Studies

Since the RF power amplifier is the major element in determining the overall performance of the RF Source, trade studies were concentrated on the power amplifier circuit. Given that a solid state circuit design would yield the high reliability desired, so the RF source would suitably complement the long life of the sulfur based electrodeless bulbs, achieving high efficiency was the high priority attribute in evaluating the RF source operating parameters and circuit architecture. Therefore, the trade-offs involved first of all the operating frequency vs efficiency followed by the semiconductor device selection, operating voltage and circuit architecture.

3.3.1.1 Efficiency vs. Operating Frequency

Efficacy and efficiency are frequently used terms throughout this report. Furthermore, efficiency is often modified to emphasize the efficiency of a particular portion of a circuit or the lighting system. In the hope of facilitating the understanding of the reader, the terms are defined below:

Efficacy - The ratio of light output (measured in lumens) to the RF input power (measured in watts) of an electrodeless bulb.

Lighting System Efficiency - The ratio of light output (measured in lumens) to the AC power input (measured in watts) of the complete lighting system (power supply, frequency source, driver, power amplifier, matching circuit, coupling device and electrodeless bulb).

DC to RF Efficiency - The ratio of the RF output power generated by a particular circuit to the DC input power into the circuit. This may apply to the final amplifier stage where it will be identified as amplifier efficiency or the entire RF souce where it will be identified as source efficiency.

Coupling Efficiency - The ratio of RF power being absored by the bulb to the RF power being supplied from the matching network.

Power Added Efficiency - The ratio of how much of the RF power is being boosted above the RF input power by the amount of DC power it takes to do this. The equation is:

$$\text{Efficiency} = \frac{\text{RF power out} - \text{RF power in}}{\text{DC power input}}$$

These Power Added Efficiency values are very pertinent for amplifiers that have a very low gain (eg. Class E). Although the RF power-out vs DC power input is very good, the amount of RF power to drive the amplifier is substantial, and it takes many watts of DC power to provide the RF drive power.

The electrodeless lamp can operate at any RF frequency. Experiments conducted by Fusion Lighting Inc. up to 120 MHz indicate that there is no significant change in bulb efficacy with frequency. Therefore, selecting an operating frequency was driven primarily by an analysis of the RF Source efficiency vs frequency. **Table 3-1** shows the calculated frequency trade offs of RF source efficiency for four ISM frequencies. There is no ISM frequency between 40 and 915 MHz. It is desirable to select an ISM Band operating frequency because the FCC regulations allow higher spurious emissions within the specified bandwidth of the particular ISM Band. However, it is not mandatory to select an ISM Band frequency if the design reduces the output of the radiated emissions to FCC specified levels. The two major factors which affect the overall performance are the DC to RF efficiency of the power stage and the RF gain of the power stage.

The analysis of circuit operation at the three lower ISM frequencies considered (13.56 MHz, 27.12 MHz, and 40.0 MHz) show that operation at 13.56 MHz offers the best efficiency of the overall power source. However, the lower the operating frequency, the higher the RF coupling losses to the bulb, the more turns the coupling coil must have (may impact light blockage) and the higher the coupling coil losses are. Based on coil loss considerations alone, one might expect slightly better overall performance at 40.0 MHz.

At the ISM frequency of 915 MHz, the DC to RF efficiency is approximately 60% and the overall gain of the power stage is approximately 15 dB. This low gain requires more DC watts to provide the RF drive power. Because the efficiency of the power supply and driving circuitry is a constant, the 915 MHz overall efficiency is a relatively poor 40.7%.

Table 3-1. Electrodeless Bulb -- Calculated Efficiency vs. Frequency

Frequency	13.5 MHz	27.1 MHz	40 MHz	915 MHz
RF Bulb Power, Watts	100	100	100	100
Coupling Loss, Watts	10	10	10	10
Combining/Impedance Loss, dB	0.2	0.2	0.3	0.5
Combing/Impedance Loss, Watts	5.18414	5.18414	7.867124	13.42203
RF Watts with Transistors	115.1841	115.1841	117.8671	123.422
Class D, DC to RF Efficiency	0.87	0.85	0.8	0.6
Power Lost in Transistors, Watts	17.21142	20.32661	29.46678	82.28135
DC Power Supplied to Final Stage	132.3956	135.5108	147.3339	205.7034
Power Gain of Transistors, dB	20	18	17	9.5
RF Input Power to Transistors, Watts	1.151841	1.825546	2.351758	13.84818
Driver, DC to RF Efficiency	0.8	0.8	0.8	0.65
Power Lost in Driver, Watts	0.28796	0.456386	0.58794	7.456712
DC Power Supplied to Driver, Watts	1.439802	2.281932	2.939698	21.30489
Power Gain of Driver, dB	22	20	20	15
RF Input Power to Driver, Watts	0.007268	0.018255	0.023518	0.437918
Xtal Oscillator DC Power, Watts	0.5	0.5	0.5	4
DC Summary				
DC Power to Final Class D Stage, Watts	132.3956	135.5108	147.3339	205.7034
DC Power to Driver and Osc, Watts	1.939802	2.781932	3.439698	25.30489
Total DC Power, Watts	**134.3354**	**138.2927**	**150.7736**	**231.0083**
AC Transformer Efficiency	0.97	0.97	0.97	0.97
Rectifying Diode Efficiency (approx. 35V)	0.97	0.97	0.97	0.97
Total AC to DC Efficiency	0.9409	0.9409	0.9409	0.9409
Watts Lost in AC to DC Power Supply	8.4379	8.686468	9.470422	14.51014
Total AC Power, Watts	**142.7733**	**146.9792**	**160.244**	**245.5184**
Total AC to RF Efficiency	**0.700411**	**0.680369**	**0.624048**	**0.407301**

On the basis of circuit efficiency alone it appears that operating in one of the lower IBM bands is an advantage. The RF source was designed so it could be operated at any of the three lower ISM Band frequencies considered by changing only a few passive component values. Operation of the demonstration circuit at a frequency of 27 MHz was chosen as a practical compromise. No significant improvement in the overall performance of the lighting system was anticipated by operating at either 13.56 MHz or 40.0 MHz.

3.3.1.2 Circuit Configuration and Device Selection

Major decisions in the RF power amplifier design involved whether to base the amplifier design on a single ended, single ended pair, or push-pull operation. In addition, consideration was given to the class of operation which would be realizable and yield the most efficient operation. See Appendix B for a discussion of amplifier operation basic concepts.

The selection of transistor type was the starting point in these trade-off studies. Initially, low cost, high frequency switching transistors operated class E were considered. Switching times of all known inverter type transistors were excessive, and high output power and high efficiency were not realizable at the same time at the selected operating frequency. DC to RF efficiencies of 80% and better could be attained in the 20W range, but relatively high drive power requirements pushed the power added efficiency of such circuits to less than 50%.

This forced the use of transistors designed for RF amplifier operation rather than high frequency switching inverter operation. The result was the achievement of power added efficiency of better than 79% at significant power levels.

The design also had to allow for suitable safety margins for voltage and current excursions during lamp start up. The transistor drain to source voltage may double during the transient impedance changes on the amplifier that accompany bulb ignition. Because of this less than optimum loading during start-up of the bulb, the circuit efficiency during steady state operation is reduced somewhat (approximately 15%) to avoid exceeding the maximum allowable voltage ratings.

Early in the investigation, it became apparent that more than a single transistor would be necessary to achieve the required power levels and power added efficiency. Push-pull operation is the most effective means of combining two transistors in one circuit. Voltage and current sharing considerations are minimized. The disadvantage of push-pull operation is a doubling of the voltage swing imposed on the transistors. This results in a lower device utilization.

The load seen by the amplifier is tuned, so that the transistors were operated with resonantly aided switching transitions. In this mode of operation, the voltage on the source of the transistors can swing between zero and twice the supply voltage, even in single ended operation.

Consideration was given to various classes of amplifier circuit operation in order to operate the RF source power amplifier in the most efficient and cost effective manner. Tests were performed with amplifiers operated in class CD, class D, and class E operation. The differences between classes involve whether the amplifier is current fed or voltage fed by its DC source, the time in the operating cycle during which the switch is on, and the nature of loading on the amplifier. A discussion of modes and classes of amplifier operation is included as Appendix B of this report.

A number of amplifier circuit configurations were built and tested in various classes of operation. **Table 3-2** summarizes the results of these tests. **Figure 3-3** shows the topologies of the various circuits referenced in **Table 3-2.**

The highest amplifier efficiency for a significant RF power output was 80%. This was obtained with a Motorola MRF 151G operating in a push pull RF amplifier circuit operating in class CD. The MRF 151G is a matched pair of MRF 151's in a single package. Earlier in the development this same MRF 151G FET yielded 68% with a sine wave drive and 74% with a square wave drive. For this particular FET and circuitry the efficiency drops slightly when operating at higher RF power levels. With a similar circuit employing a matched pair of MRF 151's in two packages, an early efficiency of 75% was achieved. Because the drive power required is very low for these RF FETs, the power added efficiency in very good. Power added efficiency is defined as the amount of RF output power generated over and above the input RF power divided by the DC power required to generate this power. The single ended MRF 151 did not produce enough power for our requirements.

Figure 3-3 b shows the basic schematic for the Class E Amplifier. This class of amplifier is extremely efficient with efficiencies greater than 90%. Basically, the class E circuit is a switching type amplifier using a square wave input. The output is tuned with a specific reactance characteristic so that the transistor switches state when the FET current and voltage passes through a zero state. Because of this, there is no DC power lost at the transition states. The output reactance characteristic is crucial to this high efficiency operation. To maintain the high efficiency the output load must be well defined and cannot change value. The variable load characteristics of the electrodeless lamp does not present a particularly suitable load for class E circuit operation.

A commercial HEX FET transistor was chosen for our class E amplifier evolution. The International Rectifier IRF 614 had the fastest switching times listed in the data book. The actual measured switching times when installed in our circuit were not as fast as stated and resulted in poor efficiency. During the switching state when current is flowing, power is consumed. Essentially, this FET is a lower frequency device. The highest DC to RF efficiency at 27 MHz achieved in class E operation was 66%, at a power output of 36.5W, with a single switching transistor operated single ended with a resistive load. This circuit required 2.8W of drive power, which resulted in the circuit's power added efficiency of only 61%.

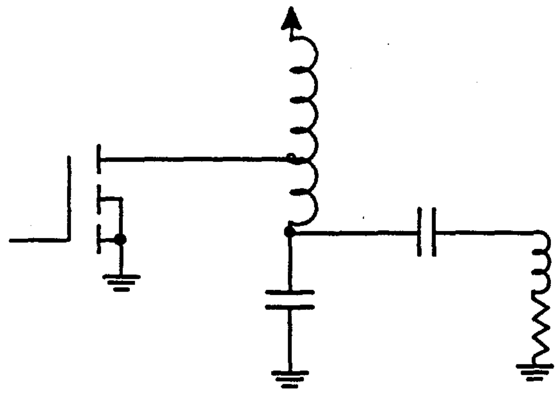
While the class E amplifier is attractive from an efficiency standpoint for many applications, it was concluded that it is not the best choice for an electrodeless lighting RF source because:

a) the variable load characteristics of the electrodeless bulb make it difficult to maintain good efficiency
b) the power added efficiency was less than that of the class CD circuit
c) several transistors would have to be combined to achieve the 110 watt output power (at 27 MHz) specified for the RF source.

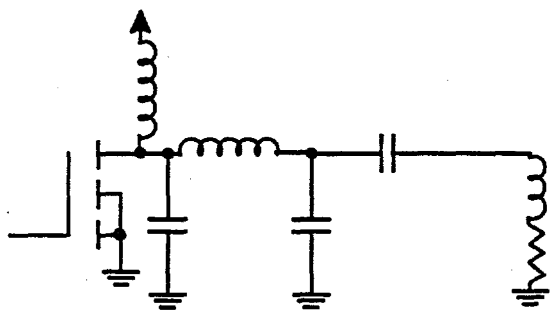
In summary, the trade-off studies led to the implementation of a push-pull power amplifier utilizing the MRF 151G power MOSFET transistor.

Table 3-2. Efficiency Measurements for Various Power Amplifier Configurations

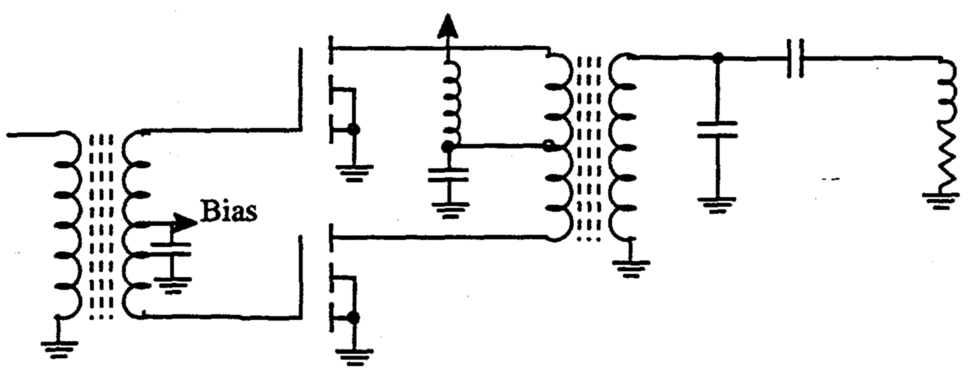
Circuit and Device	DC Power In (Watts)	RF Power In (Watts)	RF Power Out (Watts)	RF Power Added (Watts)	DC - RF Efficiency (%)	Power Added Efficiency (%)
Switching Amplifier IRF 614, Single Ended (Square Wave Drive)	55	2.8	36.5	33.7	66.36	61.27
IRF 614, Push-Pull (Sine Wave Drive)	51	5.1	32.4	27.3	63.53	53.53
RF Amplifier MRF 151, Single Ended	169	1.5	94.8	93.3	56.09	55.21
MRF 151, Push-Pull	134	1.5	100.4	98.9	74.93	73.81
MRF 151G, Push-Pull						
(Sinewave Drive)	183	1.1	124.7	123.6	68.14	67.54
(Square Wave Drive)	132	2.8	97.9	95.1	74.17	72.05
Final Optimized MRF 151G	134	0.6	108.1	107.5	80.43	79.99



3-3a Single Ended RF Amplifier



3-3 b Single Ended Switching Amplifier, Current Fed (Class E)



3-3 c Push Pull Switching Amplifier

FIG4-1.DRW

Figure 3-3. Types of Amplifier Circuits

3.3.2 Implementation

The RF power amplifier employed in the RF source is a transformer coupled push-pull circuit. It uses a single Motorola MRF151G RF field effect transistor package, which contains two matched RF field effect transistors in one package for the two sides of the push-pull circuit. As one output transistor is generating an RF current in a positive sense, the other is generating an RF current in a negative sense. Each of these output transistors are supplied DC current through an RF ferrite push-pull transformer that combines the two outputs so that their combination adds up to a single phase signal. Because of the configuration of the push-pull windings of the final push-pull transformer, the even order harmonics, (2nd, 4th, 6th, etc.) will not be transmitted through the transformer.

The drain voltage waveform, rather than being a classical half-wave sine wave as in class A-B operation, is accentuated by the even order harmonics and rings at the zero voltage baseline. The drain voltage exhibits peaking (sharpness) at the highest drain voltages. The push-pull circuit developed can operate at any of the major classes of operation (e.g., class A, B, C, D, E, or F) just by tailoring the output load and adjusting the DC bias on the gates. For this particular application, the amplifier operates as a quasi-switching amplifier. The quasi-switching amplifier takes advantage of the high efficiency capabilities of class D, E, and F operation while exhibiting the high gain capabilities of a class B and C amplifier. Appendix B provides a more detailed discussion of efficient amplifier operation.

The transistors, which have an absolute maximum drain to source voltage rating of 125V, are operated with a typical supply voltage of 30 VDC. Operation at 30 VDC voltage allows for the doubling of the voltage on the source resulting from push pull operation and provides an additional two-to-one design margin for start up voltage transitions. The average current drawn by the pair is 6 Amperes.

Figure 3-4 is a schematic of the final amplifier. The input to the power amplifier is transformer coupled from the single ended output of the buffer to the push pull drive required by the two transistors. The entire amplifier, although of a balanced push-pull configuration, operates with respect to a ground plane which is in common with the driver/buffer and the matching circuit. The output of the amplifier is coupled via a center tapped, push pull transformer to the single ended winding which connects to the input of the matching circuit. The center taps on both the input transformer secondary and output transformer primary are at RF signal ground. DC bias circuitry at both the FET input and the FET output windings provides the necessary DC bias and supply voltages.

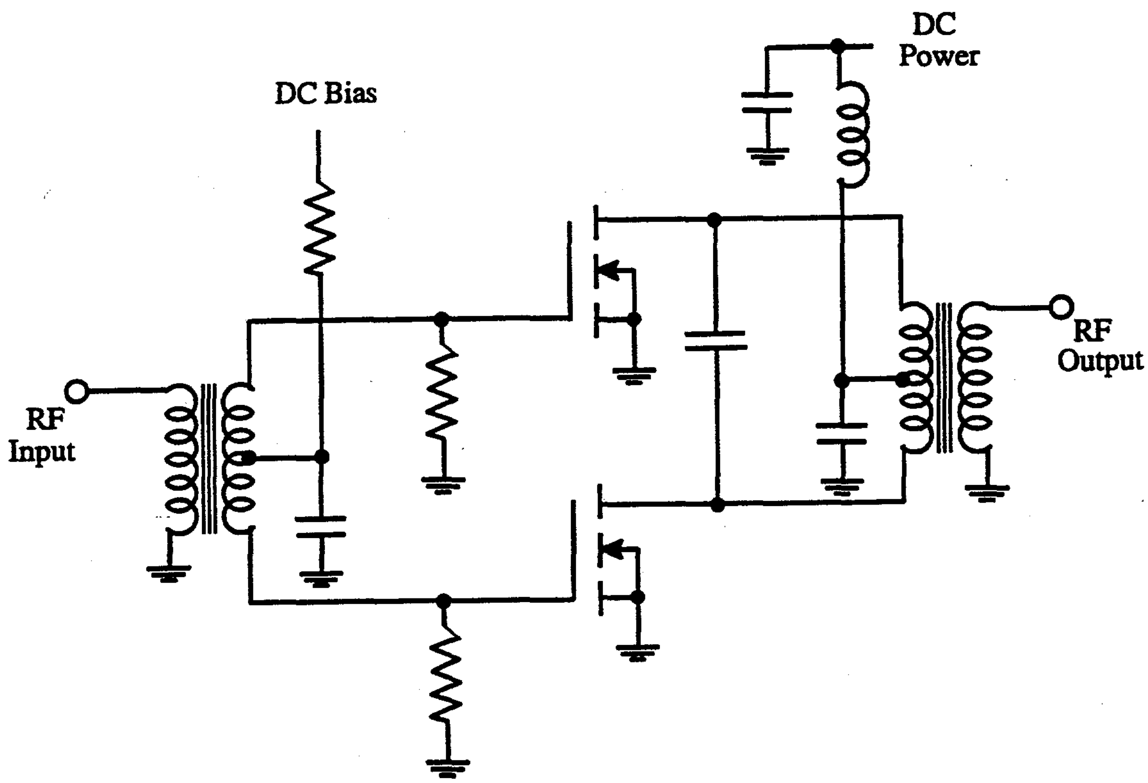


Figure 3-4. Power Amp Schematic

The output push-pull stage was developed to have the best efficiency when terminated in a constant 50 ohms. Further transformations at the bulb coupling network will transfer this 50 ohm output to the bulb's characteristic impedance. Between 100 and 140 RF watts output, the DC to RF efficiency of the output stage is 80%. When the DC power of the crystal oscillator and the buffer stage, and the driver stage is added to overall DC power consumed, the overall DC to RF efficiency is 71%. This magnitude of efficiency is considered excellent for an operating frequency of 27 MHz. **Figure 3-5** shows the RF output power of the entire RF power source as a function of the DC supply voltage. The output load is exactly 50 ohms. Below 31 volts DC, the overall efficiency is nominally 70.5%. The highest output power is 168 CW RF watts for a DC voltage of 36 volts. For this highest power measurement, the peak drain voltage was 116 volts which is near the maximum drain voltage of 125 volts for the particular FET transistor selected.

When the output is terminated in an impedance/reactance other than 50 ohms, the efficiency degrades and each drain voltage waveform becomes unsymmetrical. This impedance mismatch increases one or both of the drain voltage peaks to dangerous levels when operating at high RF output levels. Therefore, the power output is limited by the 125 volts maximum peak voltage rating of the FET output device.

The amplifier drives a tuned load consisting of the matching circuit, bulb coupling device, and bulb through an output transformer. The output transformer is a 2 turn center tapped primary with a 3 turn secondary transformer wound with two ferrite multi-aperture type cores. It is designed to have a very low leakage inductance and provides a good match of a 50 Ohm matching circuit input to the operating conditions of the amplifier.

3.4 Matching Circuit

The load characteristic presented to the amplifier is that of the coupling device and bulb as altered by the coupling circuit which bridges the two. The design selected for the matching circuit was one which provided a load characteristic for the amplifier which minimized the transistor source voltage excursions during the bulb turn on transitions and accompanying tuning and loading changes while maximizing the efficiency of power coupling to the bulb during steady state operation.

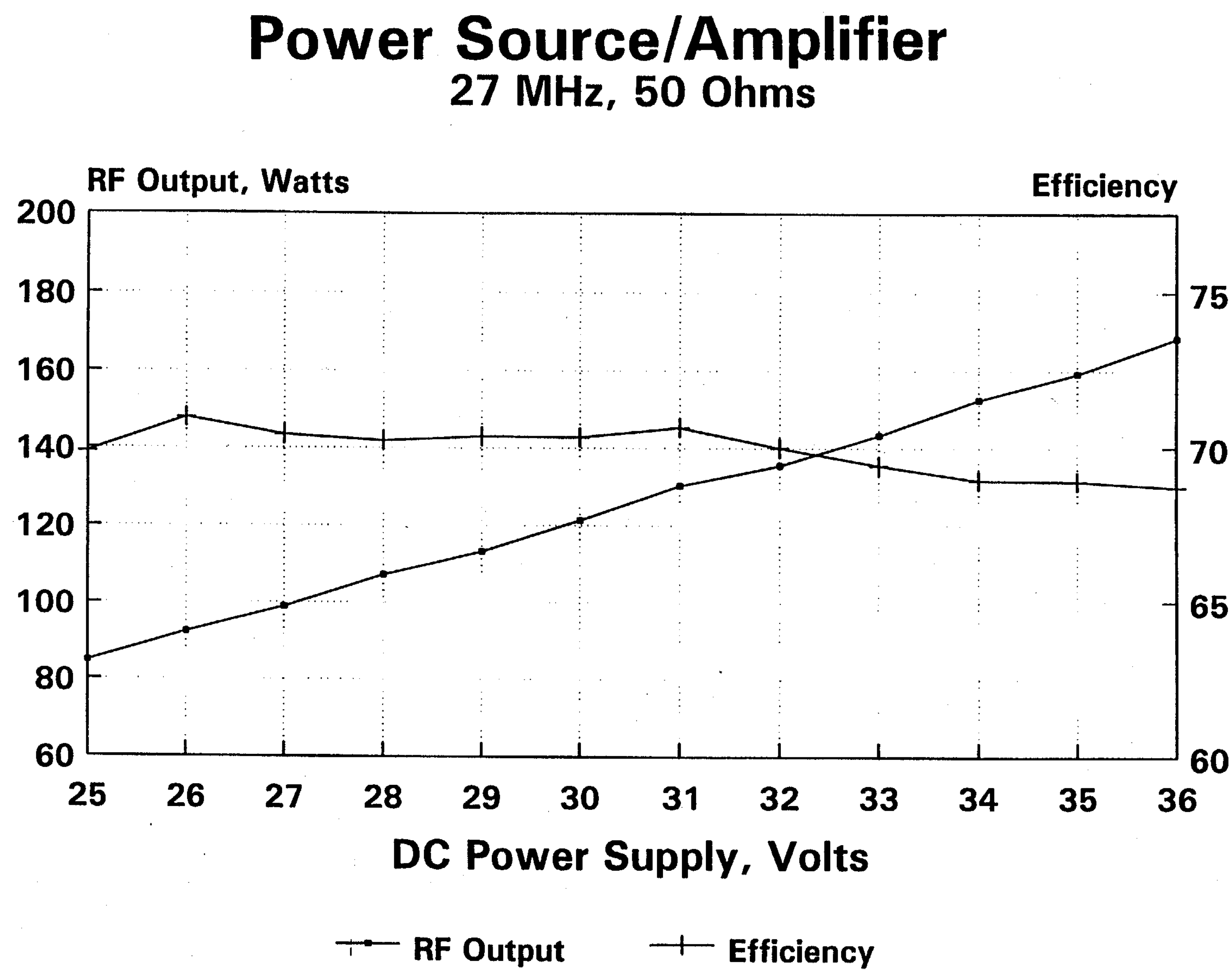


Figure3-5. RF Output Power and Efficiency vs. DC Voltage

151GAMP.CHT

When the electrodeless bulb is operating within the coil, a reactance and a resistance due to the bulb impedance is coupled magnetically to the coil. Schematically, a reactance and a resistance are added to the original coil's parameters. Its added reactance due to the one turn plasma torus within the bulb is insignificant when compared to the coil's +j 75 ohms. Therefore, the tuning of the coupling network is not changed. The added series resistance ranges from 1 to 2 ohms and is dependent upon the type fill and the pressure within the bulb.

To deliver 110 watts to the bulb, a certain RF current must flow through this added series resistance reflected by the bulb. For a series resistance of 1 1/2 ohms, an RF current of 8.5 amps is required. The power dissipated in the coil losses of 0.17 ohms (at room temperature) is 12.5 watts. A higher Q coil, or a higher reflected bulb resistance due to its fill, will result is lower coil losses. To get this amount of current to flow in the series reactance portion of the coil, 640 volts RMS must be impressed upon the terminals of the coil. The solid state RF power source cannot directly produce this amount of voltage because of the voltage rating of the output transistors. Therefore, a reactive, capacitive transformation is used to get the working voltages below the peak voltage rating of the final power amplifier transistors.

A convenient impedance level to transform down to is 50 ohms because of the bulb network startup condition. Before bulb ignition, the largest startup loss is due to just the series resistance of the coil itself. The series RF resistance is approximately 0.17 ohms. With no operating bulb impedance reflected, the capacitive transformation of the network causes the input to look like a very high impedance. If this high impedance were connected directly to the FET output stages, a large, damaging overvoltage would occur on the drains of the FETs. Because of this, the transformation network is placed 1/4 wavelength away from the RF power source using a 50 ohm coaxial cable. At a 1/4 wave length away, the high impedance startup condition is transformed to a very low impedance at the FET drains so that the resulting drain voltages are lower. The starting FET drain currents will be higher because of this 1/4 wavelength transformation but the larger currents are well within the current rating of the devices. Only the drain voltages are of concern here because they must operate near their maximum ratings to get the highest efficiency of the output FETs. When the bulb has stabilized to its steady state operating conditions, the capacitive network is tailored to have an input impedance of 50 ohms.

This 50 ohms, when placed at the end of the 1/4 wavelength cable, will still reflect 50 ohms to the RF power source.

At ignition, the plasma has not fully formed and the bulb has not heated up to its quiescent conditions. The reflected, added resistance through the capacitive transformation is very low and when transformed by the 1/4 wavelength transmission line, the impedance impressed on the FET drains is high and normally could cause a voltage problem at the drains. The VSWR of the startup at ignition state is not as poor as the pre-ignition state and the voltage step-up is not as serious. This drain overvoltage situation only lasts a short period of time when this time is compared to the "before ignition" state for which the drains have been protected. According to the manufacturer of the FET (Motorola), the FETs can withstand a very short period of overvoltage.

As the plasma reaches its quiescent state, the reactances of the capacitance transformer are set so that the input impedance to the network is 50 ohms. The RF power source has been designed to be most efficient when it is terminated in 50 ohms.

The temperature of the plasma within the quartz envelope is several thousand degrees Celsius. The outside of the quartz sphere is approximately 800 deg C. Heat radiated from the bulb and its own RF dissipation due to RF coil losses tends to increase the temperature of the exciting solenoid coil. As the dimensions of the coil increase due to the temperature rise, the inductance (tuning reactance) of the coil also increases and the tuning of the capacitive transformation is altered. This temperature related re-tuning could be compensated with temperature compensated capacitors, but the inductance change is not as severe as are the resistive losses increases within the coil.

The exciting solenoid coil is made out of copper wire. As copper increases in temperature, its resistive component increases at the rate of 4000 Parts Per Million (PPM) per degree C. This resistive increase is very significant to the heat losses in the coil. If the coil reaches the surface temperature of the bulb, a 750 degree C rise in temperature could occur. This would result in an increase of the RF resistive losses in the coil of three (3) fold. Instead of just 12 watts dissipated at room temperature the power lost in the coil at operating temperatures could be as much as 36 watts. This is a very significant design consideration.

Other noble metals for the coil conductor were considered. The lowest conductive loss of metals of Aluminum, Silver, and Gold also have a resistive temperature co-efficient of approximately 4000 PPM/C. Therefore, finding a conductor with a significantly better temperature coefficient than copper for the coil is not a practical solution to reducing coil losses.

During the bulb development, Fusion Lighting has frequently used water cooled coils to minimize resistive losses due to the high resistive temperature coefficient. The coils are simply fabricated from copper tubing. This is done mainly to allow for calorimetric measurements of the heating losses dissipated in the coil and to scientifically characterize the bulb's operating parameters. Although this water cooling is efficient, this is not a practical solution to the cooling of the exciting coil. Fusion Lighting Inc. has manufactured an appropriate copper 3 1/2 turn solenoid coil with attached, brazed copper fins which cool the coil by normal air convection. After operating this coil for approximately one-half hour, the temperature of the exciting coil was approximately 100 deg C. This small temperature rise in the copper solenoid minimizes the losses of the exciting coil.

The matching circuit which connects the amplifier output transformer to the bulb coupling device is the tuning and impedance transforming circuit shown in **Figure 3-6**. The circuit is basically a T-section impedance transforming circuit with series tuning in the output leg to tune out the reactance of the bulb and coupling device.

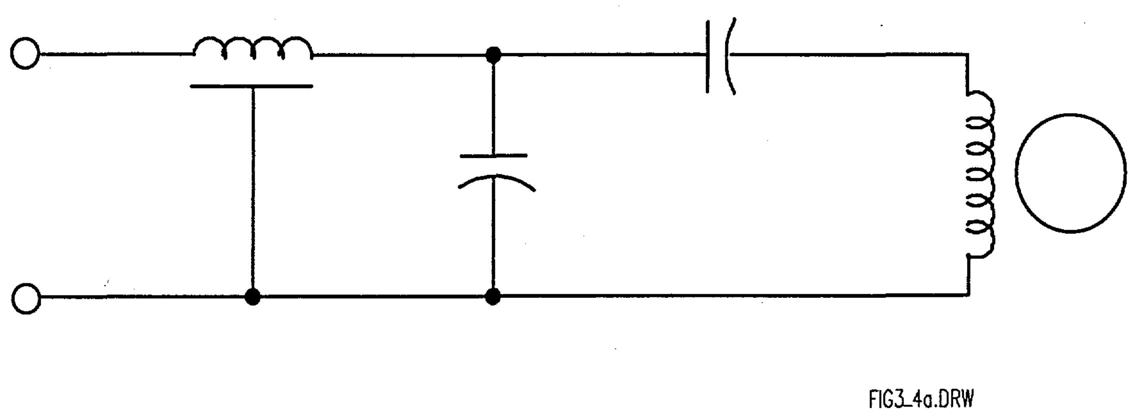


Figure 3-6. Impedance Transforming Circuit

The T-section impedance matching circuit raises the impedance reflected to the power amplifier output transformer to 50 Ohms. This impedance level permits the use of common laboratory couplers for measuring both forward and reflected power at the amplifier output. The couplers also provide a means to obtain measurements used to calculate the impedance parameters of the matching circuit and bulb parameters during all the stages of operation.

3.5 Coupling Device and Bulb Impedance

The lamp system efficiency depends upon the efficiency of the RF source, the coupling device and the bulb itself. Both capacitive and inductive techniques have been used successfully to energize electrodeless bulbs in previous bulb development work. Capacitive coupling, where the bulb is placed between two capacitor plates, requires rotation of the bulb and relatively high voltage between the plates. Care must be taken in the design to prevent arcing between the plates. Inductive coupling is implemented by placing the bulb inside a coil (typically a solenoid). Inductive coupling was chosen as the most appropriate technique for a lower power lighting system of 100 to 120 watts. Electrodeless bulbs of this power level are approximately 23 mm in diameter, and when operating at an excitation frequency of 27.00 MHz, a 3 1/2 turn coil couples to the bulb effectively. At lower frequencies, of 13.56 MHz, the number of turns have to be increased and therefore may block too much of the light output. At higher ISM frequencies, the efficiency of the RF source degrades somewhat resulting in a poorer overall lamp system efficiency.

A 3 1/2 turn solenoid coil wound with number 10 solid copper wire, with an inside diameter of 27 mm, has an approximate inductance of 440 nanoHenries. It's Q, which is the ratio of its reactance to its resistance, is 430. This is considered a very good, high number. At 27 MHz its reactance is +j 75 ohms. Therefore, its RF series resistance is 0.17 ohms. Its DC resistance is 0.0015 ohms. Since this RF resistance will result in power lost in the coupling coil, a coil design that minimizes the RF series resistance is important.

The sulfur bulb follows the well known power input relationship whereby the bulb light output improves linearly with bulb input power over the range studied from under 100 watts to over 200 watts. The bulb efficacy measurement on some of the 100 to 200 watt bulbs was as high as 130 lumens per watt with 100 watts of RF energy coupled into the bulb in an inductive coupled configuration. At higher powers, the bulb efficacy increases; at lower powers, the bulb efficacy decreases.

Using the single layer solenoids wound with number 10 gauge copper wire, the measured coupling coil loss was greater than anticipated. With 100 watts delivered to the coupling coil from the RF source, estimated coil losses were as high as 50 percent resulting in as little as 50 to 60 watts coupled to the bulb. Therefore, the bulb efficacy observed was as low as 30 lumens per watt (in the worst case) up to 60 lumens per watt. To reduce the high coil losses, a design to improve the convection cooling of the coil, while maintaining low interturn capacitance, was conceived and fabricated by Fusion Lighting for the final configuration as can be seen in **Figure 1-1**.

An examination of the load impedance variation and how it might be adjusted at the amplifier matching circuit output were addressed early in the amplifier investigation as well as during bulb development (not part of this NICE[3] project). This included an analysis of inductive coupling and measurements on various coils and lamps by Fusion Lighting.

Appendix A summarizes an analysis of inductively coupled bulb excitation in terms of electrical impedances presented to the RF source power amplifier matching circuit. Conclusions which follow from this analysis are that the effectiveness of coupling power to the bulb inductively is a function of four factors relating the coupling coil and bulb. These are:

- Bulb effective Q
- Coupling coil Q
- The coefficient of coupling between the coil and bulb
- Frequency of operation

During the development of the RF source, careful attention was given to each of these factors by Fusion Lighting in the bulb-to-RF source interface.

4.0 RF SOURCE TEST DATA

4.1 RF Source Developmental Test Performance

A breadboard assembly of the RF source with a push pull RF power amplifier was constructed and subjected to tests with various forms of simulated and actual bulb loading. The circuit for the breadboard was essentially a composite of the circuitry in **Figures 3-2, 3-4, and 3-6.** The results of these tests were then applied to development of the final RF source and bulb assembly shown in **Figure 1-1.**

4.1.1 Optimal Loading

Results obtained with the RF source, without the coupling circuit, terminated in an optimal loading resistive load of 50 Ohms are summarized in **Figure 4-1.** This is a power flow diagram which shows signal power levels and power loss to heat throughout the circuit when operated at 110W into the resistive load. The total power loss to heat is 46 watts. The overall DC to RF efficiency is 70.5%. The power amplifier efficiency is 79%. The crystal Oscillator and the Buffer stages in this configuration consume an excessive amount of DC power (17 watts), mainly because we utilized off-the-shelf components. The TTL crystal Oscillator Chip had to have a regulated voltage of 5 VDC and drew 90 ma. The gate bias voltage for the power amplifier also had to be regulated with a Zener voltage to maintain its constant gain characteristic over a varying range of DC supply voltage. With further driver circuit development, the 15 watts of heat can be reduced to 4 or 5 watts.

With the power source terminated in a constant, optimal 50 ohms, a plot of RF power output and DC to RF efficiency is plotted versus the DC supply voltage. These two plots are shown in **Figure 3-5**. The maximum RF power output of 168 watts occurs at a DC source voltage of 36 volts. The limiting factor for this maximum point of operation is the drain to source voltage of 125 volts peak.

Figure 4-2 incorporates the matching circuit and a temporary three and a half turn coupling coil in place of the 50 Ohm termination. As a bulb simulation, a one Ohm resistive load is placed in series with the coupling coil to simulate the steady state load reflected back into the coupling coil by a hypothetical coupling device and bulb. This is equivalent to the circuit being

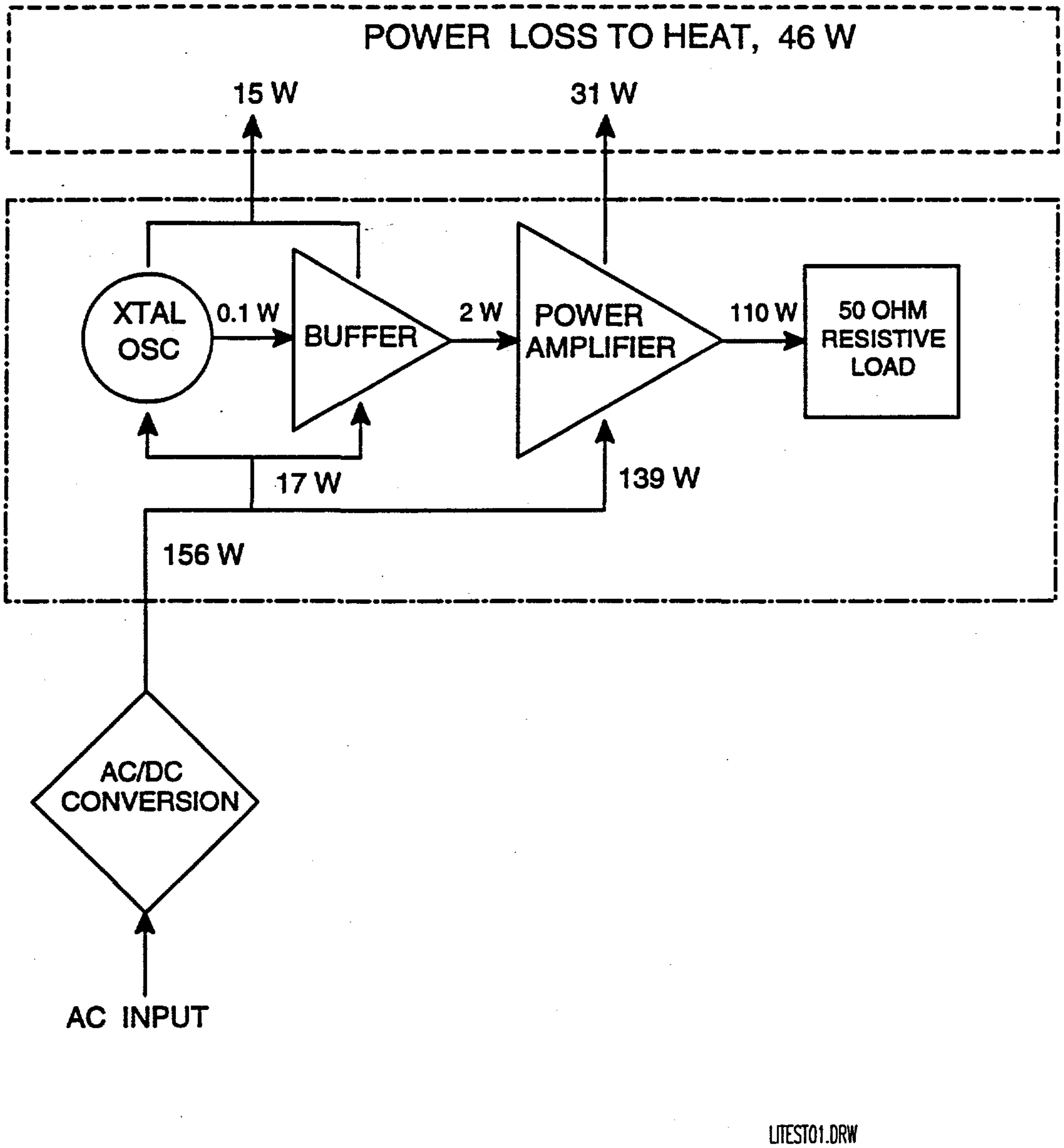


Figure 4-1. Power Flow Diagram for Developmental RF Source with Optimal Loading at Power Amplifier Output

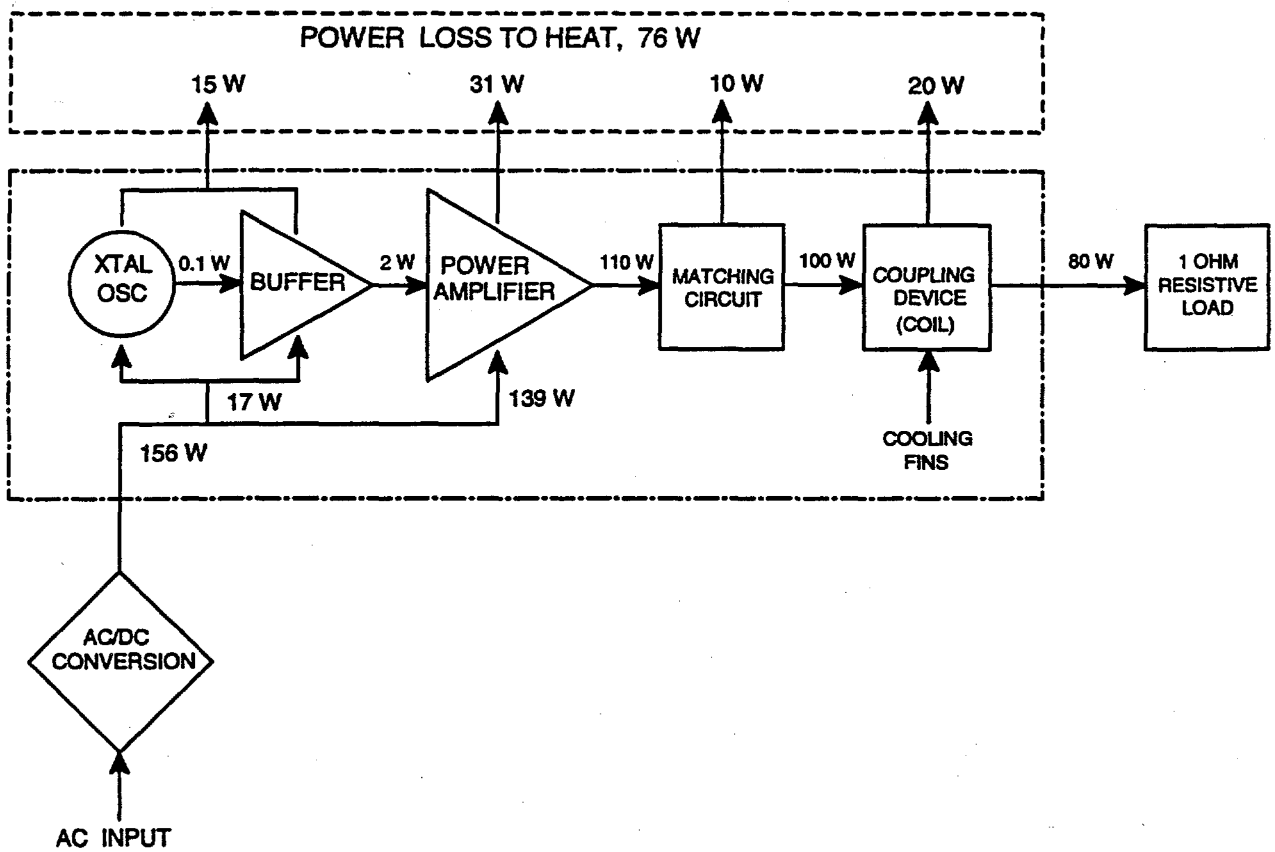


Figure 4-2. Power Flow Diagram for Developmental RF Source with Optimal Loading at Coupling Device

optimally loaded. The 50 to 1 ohm matching circuit consumes approximately 10 watts. The copper 3 1/2 turn coil consumes approximately 20 watts. This power loss increases its temperature and the losses in the coil increase significantly. Cooling fins are attached to the coil to keep its temperature down. 80 watts of RF power is delivered to the one ohm simulated load. The total power loss to heat is 76 watts.

4.1.2 Bulb Loading

Results obtained with the NICE[3] RF source driving a bulb through a lamp coupling device and matching circuit are summarized in **Figure 4-3.** This is a power flow diagram which shows signal power levels and power loss to heat throughout the circuit when operated at 110W into the lamp coupling device for a particular bulb as the circuit load. 75 watts are supplied to the bulb. The power lost to heat is 81 watts. The matching circuit still consumes only 10 watts but the losses in the coil increase from 20 to 25 watts due to the temperature rise in the copper coil temperature. This temperature rise is caused by the heat radiated from the bulb within the coil. The temperature resistivity of copper (along with silver and aluminum), is 4000 ppm / deg C. Therefore, it is imperative to cool the coil to minimize coil losses.

Test bulbs provided for operation with the RF source yielded measured light outputs of approximately 3,000 Lumens at 100W into the matching circuit, or 30 Lumens per Watt. This poor performance was accounted for by excessive losses between the coupling coil and bulb. Also, most of the bulb's performance numbers were characterized at a higher RF power level than 100 watts. If the bulb resistance reflected back into the coupling coil were the five Ohms as originally understood instead of the one Ohm measured above, and if the RF coil resistance were 0.25 Ohms, the losses in the coil would be reduced from 25 watts to 5 watts. Refer to Appendix A for further details.

4.2 Final RF Source Test Performance

The entire circuitry from the DC input to the bulb is shown in the schematic of **Figure 4-4**. This is the working schematic and it incorporates all of the sub schematics discussed earlier. The entire schematic up to the delay line was fabricated on a single PC board which is displayed in the photo of **Figure 1-2**. The matching circuit and the delay line are incorporated inside the housing and the coupling coil and the bulb are outside the housing. Power measurements were made via a directional coupler inserted bnetwee the power amplifier and matching network. When the bulb reached its steady state, measurements confirmed that 110 to 120 RF watts were delivered to the matching circuit as shown in the power flow diagram of **Figure 4-3.**

<u>Summary of Test Results</u>

Frequency of operation	27.00 MHz
DC input voltage	25 to 35 volts, 28 volts nominal
RF output to matching circuit	110 watts min
DC to RF efficiency (with bulb operating)	70%

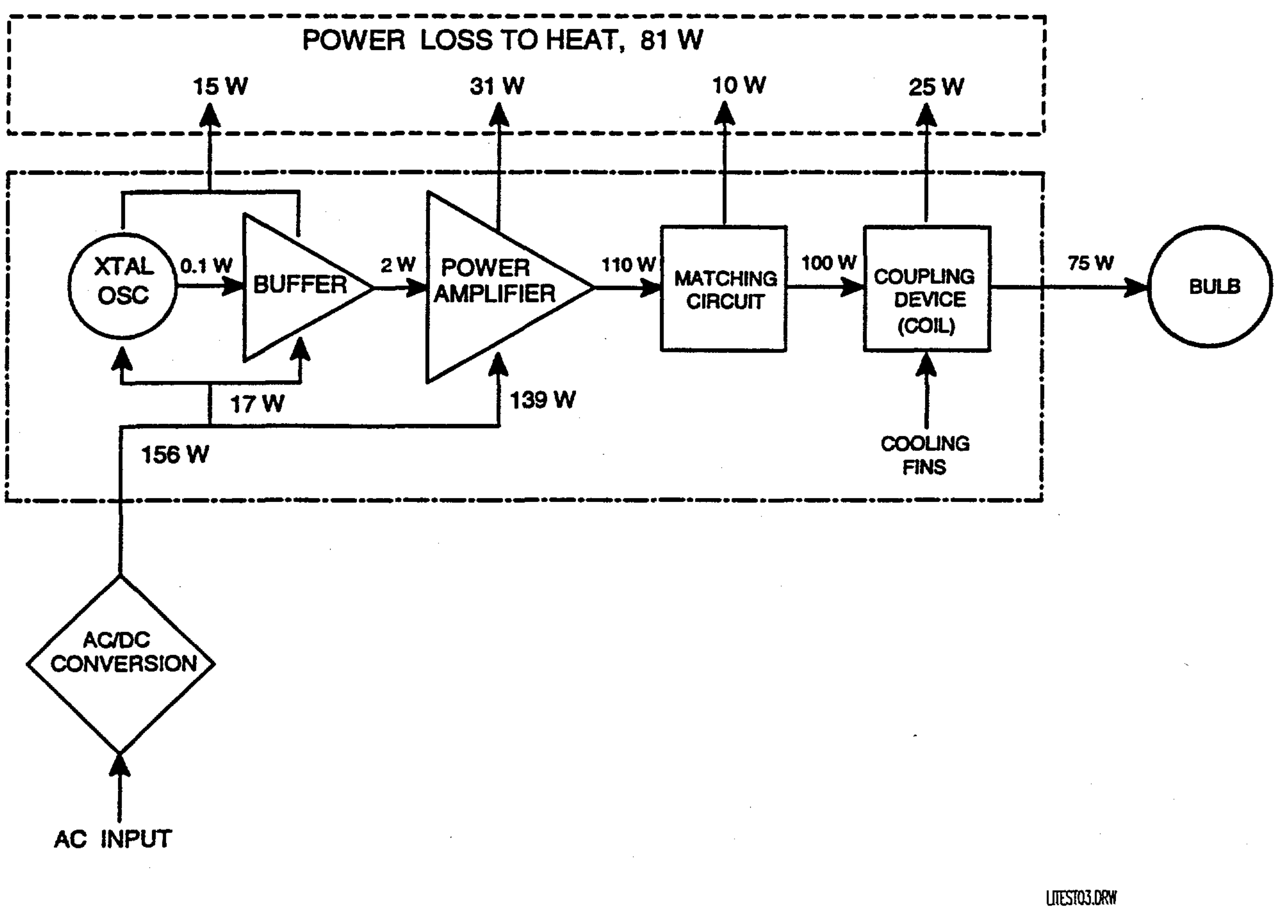


Figure 4-3. Power Flow Diagram for Developmental RF Source with Bulb Loading

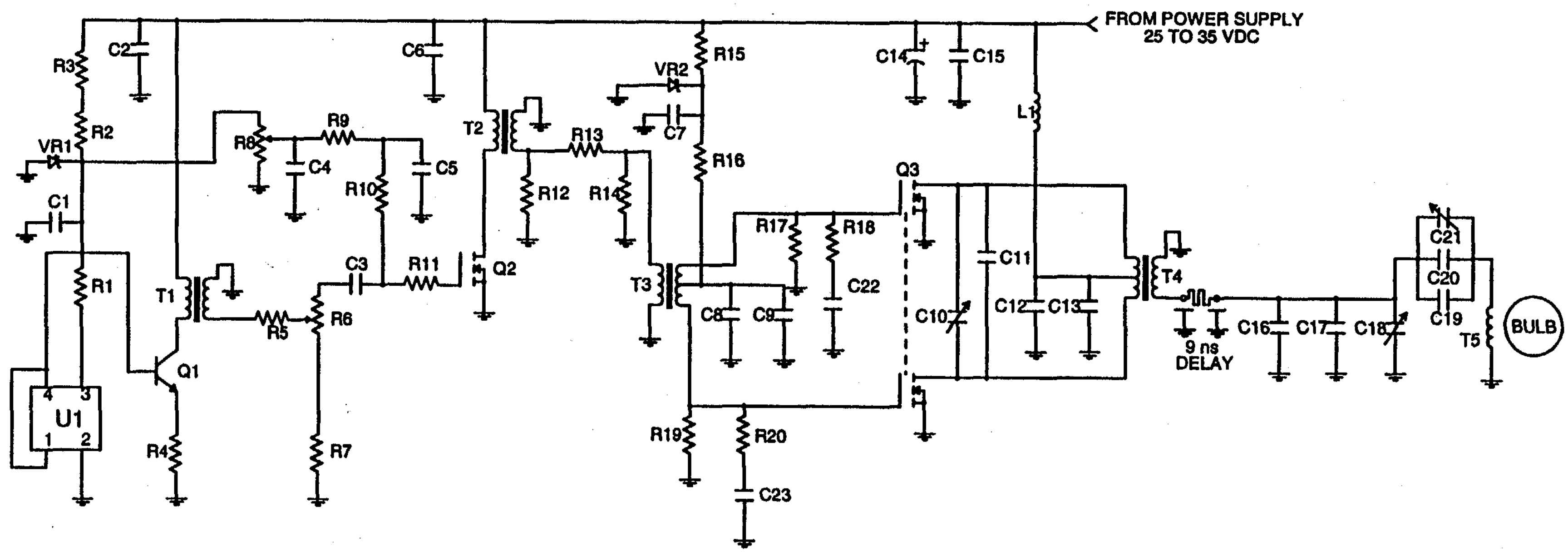


Figure 4-4. Schematic of Final Test Circuit

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

At the beginning of this NICE[3] program to develop a solid state RF source for electrodeless lighting, performance goals were set for an RF source assembly which contains all of the electronics up to a coupling device and the electrodeless lamp. The two key parameters which drove the RF source design were efficiency and output power.

The efficiency goal for the RF source was established as 80% - a recognized challenge but nevertheless one which was deemed achievable. This efficiency, if achieved would contribute significantly to realizing the desired energy savings potential of the sulfur based electrodeless lamps being developed by Fusion Lighting Inc.

The power output goal was determined by taking the 100 watt bulb requirement baseline and adding the 10 watts estimated at the beginning of the program to be dissipated in a coupling device by Fusion Lighting. Hence, the minimum specified RF output power to be delivered by the RF source was 110 watts.

The DC to RF efficiency actually achieved by the RF source was approximately 70% overall although the final output stage of the RF source does achieve 80% efficiency when operated into a 50 ohm load. Although the 70% efficiency of the RF source as presently implemented with the schematic illustrated in **Figure 4-4** does not meet the original somewhat difficult goal of 80% overall, it does represent a significant achievement at this stage of development. Furthermore, there are circuit modifications that, if implemented, can increase the efficiency and certainly approach the 80% goal. These improvement concepts will be discussed below.

The RF source output power goal of 110 watts delivered to the coupling device was achieved under all operating conditions with the test bulbs supplied. As much as 168 watts of RF power was achieved under conditions of 50 ohm loading. From a practical engineering point of view, the load variation of the bulb limited the output to a safe operation in the 110 to 120 watt range.

The RF source was packaged in a self contained unit containing the oscillator driver, output amplifier, and matching network all located in one package. The package was also convection cooled which is a desirable feature for nearly any application.

Evaluating the RF source with the coupling coil and the electrodeless bulb as a lighting system without specially designed fixtures, reflectors, etc., the light output measurements show a range of 30 to 60 lumens per RF watt delivered by the RF source. Two factors were found to create this lower than expected performance. First, analysis and tests revealed that the losses in the coupling coil exceeded the 10 watts of loss originally predicted. The loss was actually 2.5 to 3 times greater that the original predictions. Analysis showed that the loss had two contributors - the self induced I^2R loss resulting from the RF energy being coupled by the coil to the bulb and additional losses created as a result of the thermal energy radiated from the bulb surface and absorbed by the coil. The latter factor resulted in an increased temperature of the copper in the coil. The increased temperature resulted in an increased coil resistance which further increased the power loss in the coil. A second factor contributing to a lower than anticipated lumens per RF watt of the RF source, coupler, and bulb is attributed to the particular characteristics of the specific bulbs tested. A review of the Elenbaas curves for the lamps tested shows that the test bulbs achieve a higher efficiency at higher RF input powers than the RF source was designed to deliver. Data taken by Fusion Lighting indicated that the efficacy of some bulbs ranged from 60 to 100 lumens per watt with 100 watts input and even higher efficacies were demonstrated at higher inputs. As previously stated, the coupling coil loss reduced the power actually delivered to the bulb to as low as 50 to 60 watts. Hence, as expected from the Elenbaas curves, the light output in lumens per watt from the test bulbs was lower than expected. In general, the higher the bulb is operated on the Elenbaas curve, the higher the efficiency will be. Since the actual operating point was lower on the curve, the optimum (highest possible) efficacy of the bulbs was not observed during tests with the RF source.

In summary, the conclusions drawn from the development of the solid state RF source and its operation with available sulfur based electrodeless lamps are:

- The RF source as implemented achieved a circuit efficiency of approximately 70%.
- Circuit improvements can raise the RF source efficiency to approximately 80%.

- The RF source reliably operated with widely varying load conditions reflected to the output amplifier stage by the coupling coil and bulb.
- The convection cooled self contained RF source package is a positive asset for most applications.
- The coupling coil losses were higher than originally predicted which means that a revised coil design that allows it to operate at a lower temperature must be accomplished to achieve an improved lighting system efficiency.
- The choice of operating frequency is a trade off of circuit efficiency vs coupling device efficiency. The lower the operating frequency the higher the circuit efficiency but the lower the inductive coupling efficiency.
- The bulbs utilized for testing the RF source had efficacy characteristics which were not the optimum match for the RF source although the RF source was capable of exceeding the power output design goal. In this sense, the test results do not demonstrate the electrodeless lamps tested at the best advantage of their capabilities.

5.2 Recommendations

The experience acquired in the development of a solid state RF source leads to the following recommendations:

Task 1 Utilizing a higher voltage semiconductor device in the RF source output stage will definitely improve the circuit efficiency. The higher voltage device would allow the voltage transformation from the AC power line to the relatively low DC voltage necessary to utilize available silicon transistors to be eliminated. The most likely candidate semiconductor device to provide this capability is a Silicon Carbide (SiC) transistor which is not only a high voltage device but offers higher power density per device than silicon transistors and can operate at very high temperatures. The latter feature can be very attractive for certain lighting applications. While the potential advantages of SiC devices were recognized even at the time the development the solid state RF source was proposed as a NICE[3] program candidate, recent advances in SiC transistor technology make this design change to the RF source a low risk modification.

Task 2 Changing the circuit architecture by converting the power amplifier into a power oscillator and eliminating the oscillator/driver stages will also improve the overall efficiency. This eliminates the losses associated with these circuits including the losses due to the additional voltage transformation to the low DC voltages necessary for the crystal oscillator and the driver/buffer amplifier.

Task 3 While items 1 and 2 address efficiency improvements of the RF source circuitry up to the coupling coil, the test results indicate that to further improve the overall lighting system efficiency, improvements in the coupling coil design are also important. The primary emphasis on this task would be focused on heat removal from the coil. Experiments (not part of this NICE[3] project to develop a solid state RF source) with water cooled coils indicate substantial coupling improvement when the temperature of the coil is reduced. While controlling the temperature rise in the coil, the goal would be to minimize the interturn capacitance of the coil (as was accomplished in the final coil design tested at the end of the current program), and of course, to minimize the amount of light output which might be blocked by the physical structure of the coil.

To summarize the recommendations, further development utilizing SiC transistors and a pulsed power oscillator architecture should enable the 80% efficiency goal of the RF source originally desired to be achieved.

APPENDIX A
BULB AND COUPLING DEVICE ANALYSIS

General Coupling Theory

This analysis summary is based upon inductive coupling of energy to a sulfur based electrodeless bulb through an external coil. Other possible forms, such as capacitive coupling, would impact on the RF source matching circuit, but would not have a significant impact on the RF power amplifier itself.

When a sulfur based electrodeless bulb is excited by an external coil, coupling of energy into the bulb is by transformer action as described with reference to **Figure A-1a.** The primary of the transformer is the exciting coil. The secondary of the transformer is a closed circular path or loop within the exciting coil which is in the same plane as the exciting coil. The voltage induced around any secondary loop is equal to the per turn voltage on the primary coil. The current which flows in a secondary loop is the induced loop voltage divided by the effective resistance around the particular loop path. If no current flows in any loop with the secondary domain, the induced outer diameter of the secondary is the diameter of the primary coil.

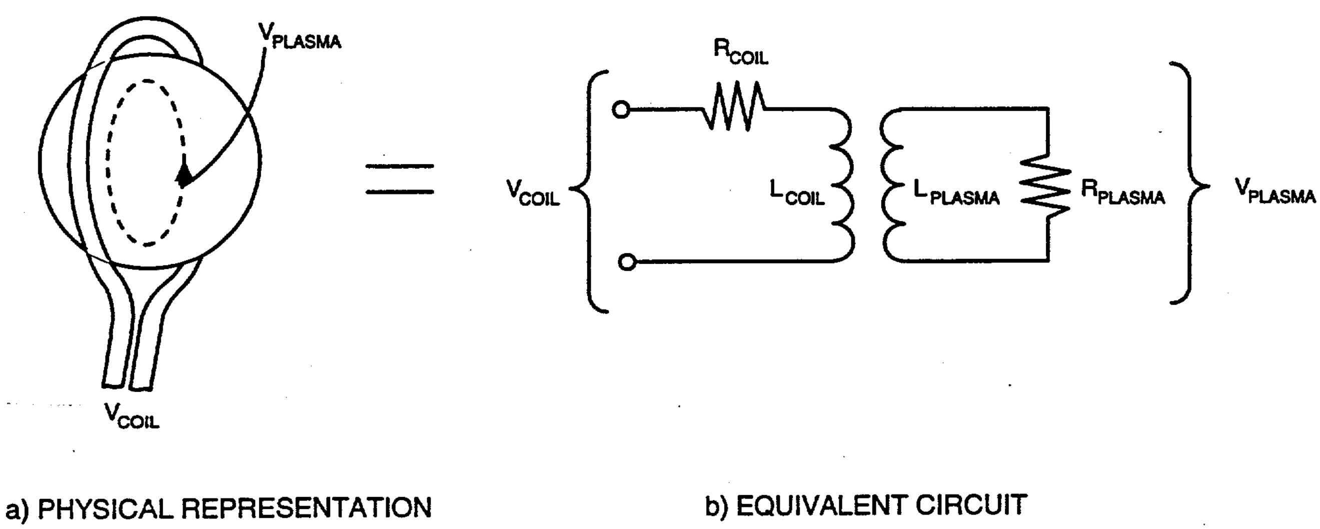


Figure A-1. Inductive Coupling to a Bulb Plasma

As ionization occurs within the bulb due to electromagnetic field heating, current flows in a closed loop in part of the secondary domain which is within the bulb. The diameter of the resulting loop of current flow within the bulb is such as to enclose the maximum cross sectional area of exciting magnetic field. This is countered by cooling of the bulb surface temperature which limits ionization near the inner surface of the bulb.

When an ionized loop current flows within the bulb, a glowing torus forms which is indicative of the conducting path within the bulb. The diameter of this visible torus is initially the maximum which the thermodynamics of the bulb due to surface cooling permits. As the bulb heats further, the sulfur based elements are brought into the plasma to produce very bright light emission of the desired spectrum. from a diffused region of the bulb. Current flow in this torus counters much of the magnetic field within the torus which causes the toroidal diameter to shrink. Stability is reached within the bulb when the voltage drop around the torus is sufficient to minimize further build up of toroidal current and further collapse of the torus due to cancelled magnetic field. This is the operating equilibrium condition of the lamp. If this equilibrium is not reached because of low resistance around the loop in the bulb fill medium, then the plasma will pinch off and the bulb darken and go off.

Figure A-1b is an electrical equivalent circuit of a lighted bulb and coupling coil in their steady state, light producing mode of operation. The primary of the transformer is the exciting coil, having a self inductance of L_{coil} Henries and a loss resistance of R_{coil} Ohms. The secondary of this transformer is a toroidal current loop within the bulb, whose path resistance of R_{plasma} Ohms and inductance L_{plasma} Henries are determined by the size and fill of the bulb. Mutual coupling, defined by the coefficient of coupling k, exists between the coil and the virtual secondary, defined by the relationship between the dimensions of the exciting coil and the secondary current loop within the bulb.

Impedance - In terms of the parameters in **Figure A-1b**, the impedance, looking into the coupling coil at its terminals, during steady state lighted operation, is given by

$$Z_{IN} = R_1 + \tau R_2 + j(2\pi f L_1 - \tau 2\pi f L_2)$$

where R_1 is the coupling coil resistance in Ohms,

R_2 is the virtual resistance of the torus within the bulb, in Ohms

L_1 is the self inductance of the coupling coil in Ohms, and

L_2 is the virtual inductance of the torus within the bulb, in Ohms.

The effective coupling factor τ is given by

$$\tau = [kQ_2^2/(1 + Q_2^2)]N_1^2$$

where Q_2^2 is $2\pi f L_2/R_2$, and

N_1 is the number of turns on the exciting coil.

Coupling Efficiency - If the imaginary part of the coil impedance relationship is tuned out, the coupling efficiency of the coil to the lamp η is given by

$$\eta = \tau R_2/(R_1 + \tau R_2),$$

and approaches unity as τR_2 increases without bounds. The product τR_2, which can be written as

$$\tau R_2 = [Q_2/(1 + Q_2^2)][2\pi f L_2]kN_1^2,$$

is maximized as all terms in this relationship are maximized. The term $Q_2/(1 + Q_2^2)$ which is plotted in **Figure A-2**, has a maximum value of 0.5, which occurs when Q_2 is unity. All other terms in the relationship increase without bounds.

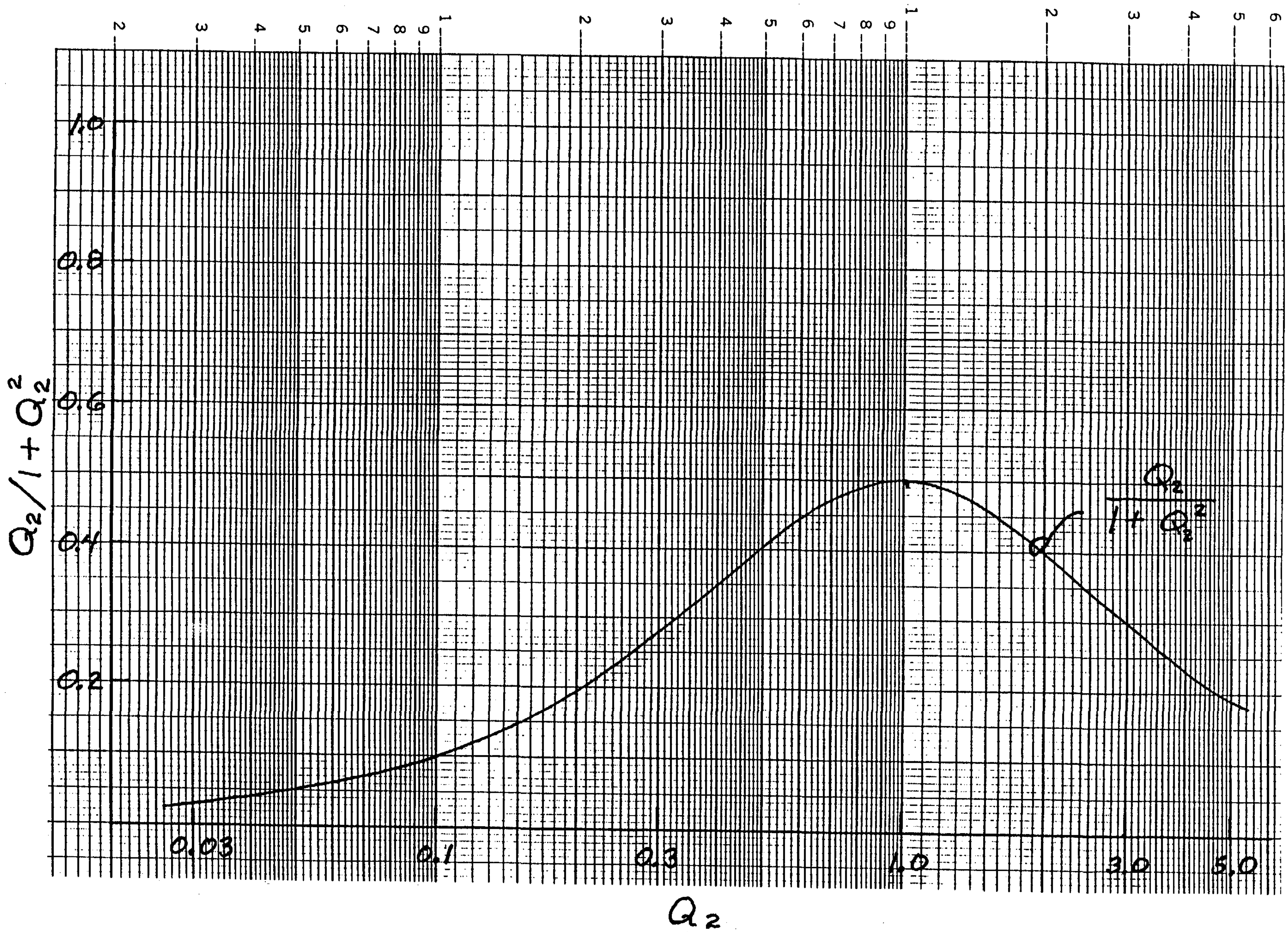


Figure A2. $Q_2/(1 + Q_2^2)$ is Optimized at $Q_2 = 1.0$

Maximum coupling efficiency is achieved when Q_2 is as close to unity as possible, when operating frequency is as high as possible, when the coefficient of coupling is as close to unity as possible, and when the number of turns on the coupling coil is maximum.

Coupling Device Measurements and Analysis

Since the coupling coil Q is one of the parameters that controls the coupling efficiency, coils of different cross-sectional geometries were meausred for comparison. The coils were single layer solenoids of five turns each, 30 mm in diameter and 50 mm long. The Qs were measured at 27 MHz. The results were:

Wire Cross Section Geometry	Round	Square	Rectangular
Measured Q	268	55	751

Clearly, the coil with the rectangular cross-section would be the best choice for a coupling coil conductor all other factors being equal.

To gain further insight into the understanding of a coupling coil design, an analysis of the coil's current distribution was investigated. This was accomplished via finite element analysis based upon Maxwell's equations. Analyses from three different vendors of electromagnetic software were obtained on a variety of different coil designs. In general, the results did not compare favorably with the Q measurements taken on the coils carefully manufactured to the same design by Fusion Lighting. While the inductance measurements were comparable, the calculated resistance values from the software analysis were significantly lower (from 30-50% lower) than the Q measurements indicated. Had the resistive component of the coil and its corresponding coil current calculation from the analysis been achieved in the physical coil hardware, the losses in the coils would have been significantly lower. One additional aspect of the finite element analysis worth noting is that none of the three analytical programs used accounted for the interwinding capacitance of the coil. It is concluded that it is desirable to minimize the interturn capacitance in the design of a coupling coil and this conclusion is in agreement with other practitioners in the field.

Bulb efficacy - **Figure A-3** shows the trend of steady state bulb light output in Lumens as a function of RF power inductively coupled to the bulb in Watts. This is called an Elenbaas curve and can be plotted with a best fit straight line vs Net RF Power to the Bulb. This plot shows that an initial power input of P_i Watts (25 watts) is required before any visible light is produced. Although the plot intersects the zero (0) lumens axis, this theoretical RF power is not a true mode of operation. Most importantly, as the RF power is increased to a nominal initial steady state operating point within the bounding data points, the visible light output increases with power input at a rate which is faster than the RF power input rate. The result is that the light producing efficiency or efficacy of the bulb increases with power input.

The impedance presented to the RF source coupling circuit by the bulb through the coupling device changes with this change in RF power input because the plasma temperature changes and the effective resistance of the virtual secondary changes. Since this impedance is working against a circuit loss impedance, this will have an effect on overall circuit RF power to light efficiency.

Transitional impedance - **Figure A-4** is a representation of the volt-ampere characteristic of the electrodeless bulb. This characteristic is divided into three regions; pre-ionizing, ignition, and plasma discharge. During the pre-ionizing period, bulb voltage must be driven to the ignition point, which corresponds to a high voltage across the coupling coil sufficient to force an ionizing current to flow in the bulb. During ignition, voltage falls to that of the plasma state over which voltage is relatively constant.

These varying conditions represent the different load impedances impressed on the RF source as the bulb is turned on and reaches its normal operating state. The normal operating point of the amplifier must be set such that the voltage and current ratings of the active devices are not exceeded during turn on of the bulb.

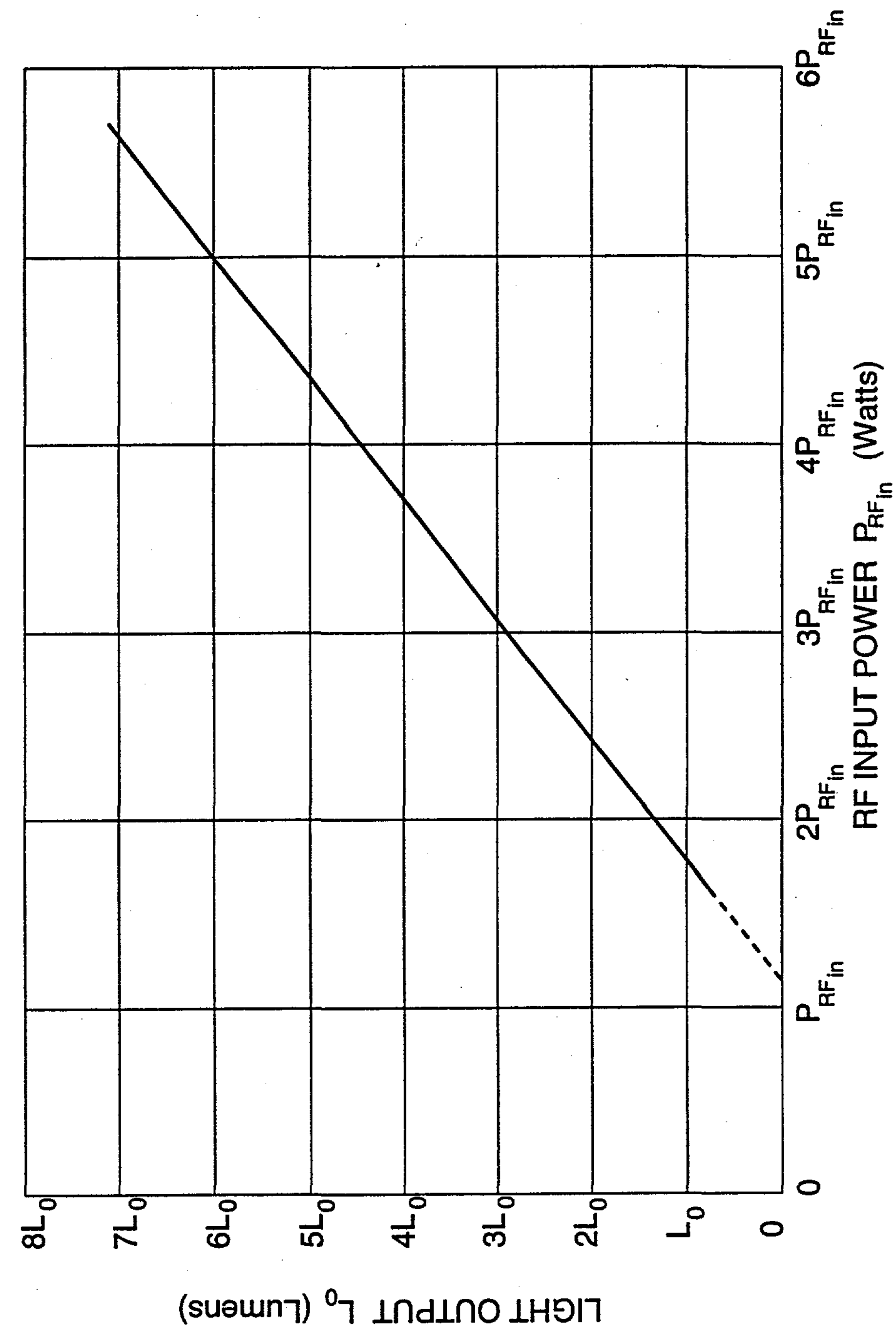


Figure A-3. Representative Elenbaas Curve

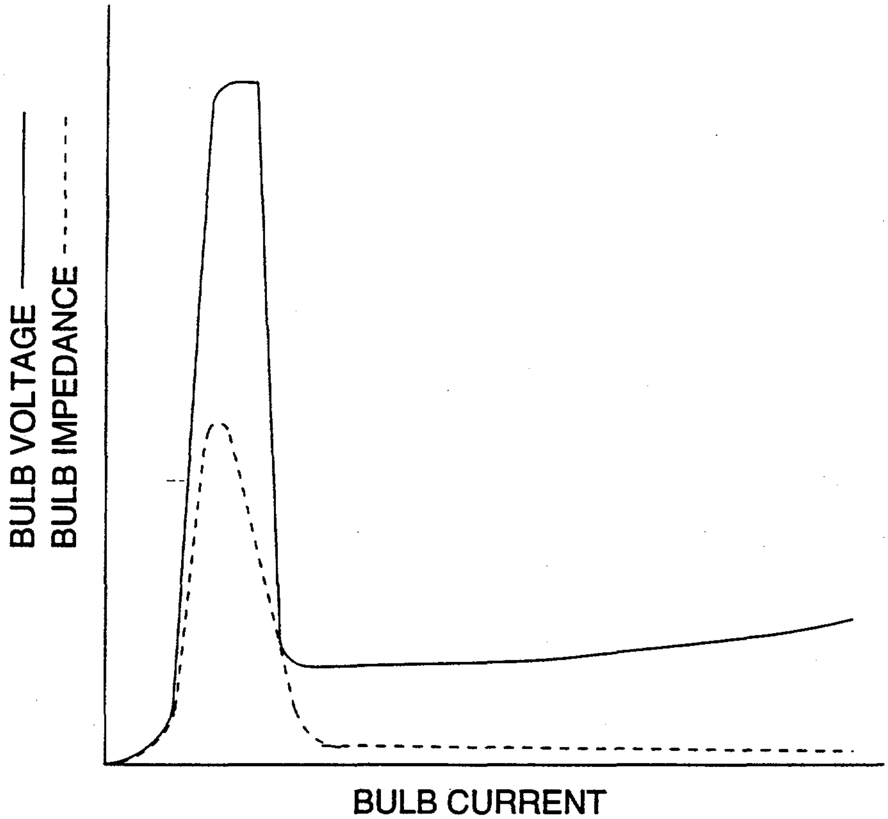


Figure A-4. Bulb Voltage and Impedance vs. Bulb Current

APPENDIX B
AMPLIFIER OPERATION

Modes - The most efficient amplifier types are those which are operated in a switching mode with circuit aided commutation. Potential switching losses are stored in reactive components and energy is recovered between switching periods. In general, the load circuit is resonant in some sense and therefore such amplifiers are narrow banded.

Configuration - Amplifiers may employ active devices in either single ended or balanced configurations. A single ended amplifier is an amplifier operated with a single active device operating to supply power only during one half cycle of RF output. Single ended pairs of devices may be operated alternately to yield a full wave output. Multiple devices may be employed to make up the single active device function. In general, single ended amplifiers operate unbalanced with respect to a ground plane. **Figure B-1** illustrates the topological differences.

Class of Operation - Amplifier operation is commonly described in terms of the class of operation, which denotes the mode of operation of the active devices. Included in this is whether the amplifier is operated single ended, in single ended pair modes, or push pull. Three classes of operation were considered as approaches to switching amplifiers for the RF source; class D (single ended Pair and push-pull), class E (single ended), and class CD or F (push-pull). The dominant characteristics of the three classes of operation are illustrated in **Figures B-2** through **B-4** for circuits operating with switches which are ideal except for switching time allowances.

Class D - As indicated in **Figure B-1**, each of the two switches are closed alternately for a full half cycle of operation. Although single ended class D circuits do exist, the most effective active device utilization is in pairs as illustrated in the two examples in **Figure B-1** and **Figure B-2**. Closure and opening of the switch occurs at current zeroes with initial voltage provided by

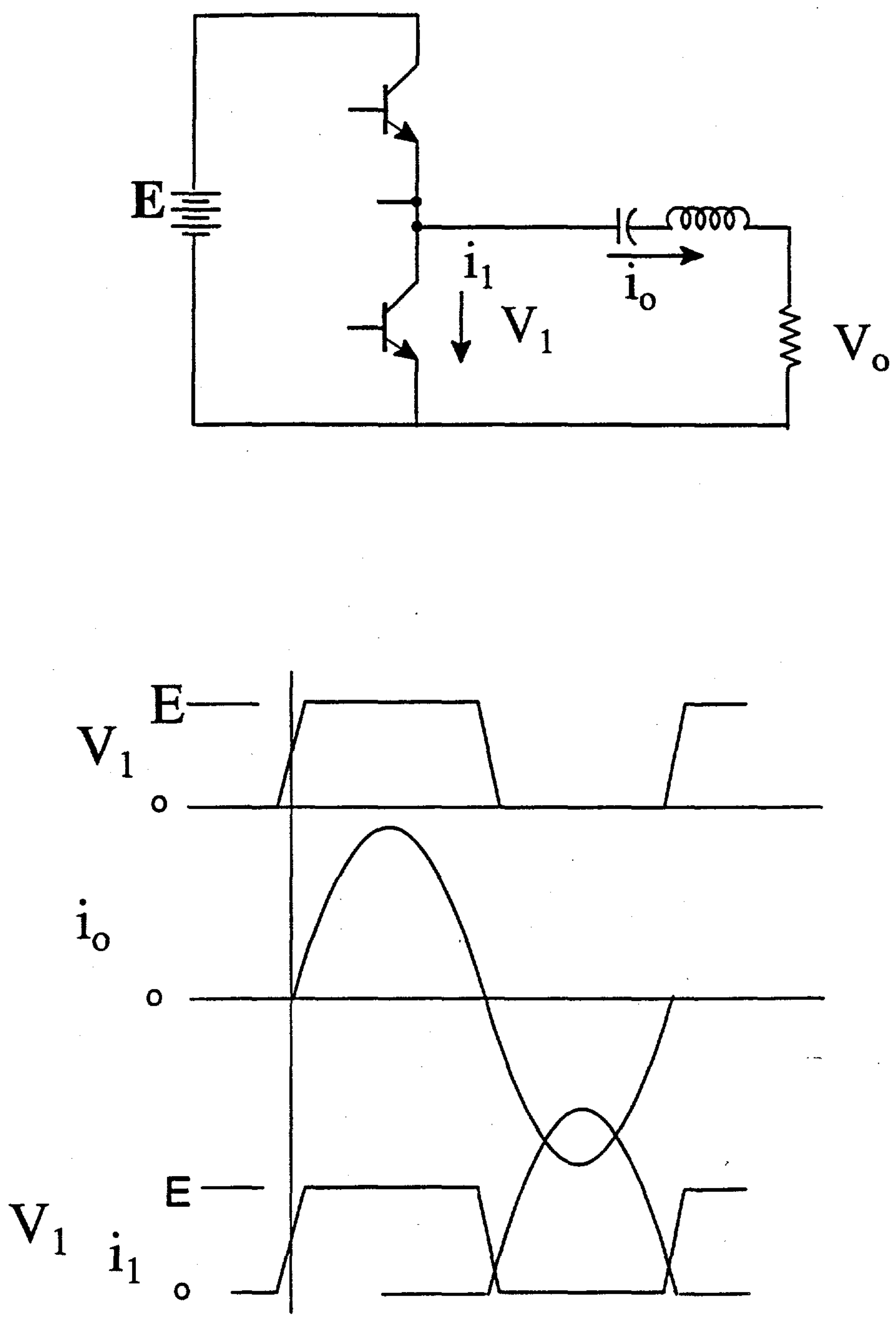


Figure B-1. Class D Operation -- Single Ended Pair

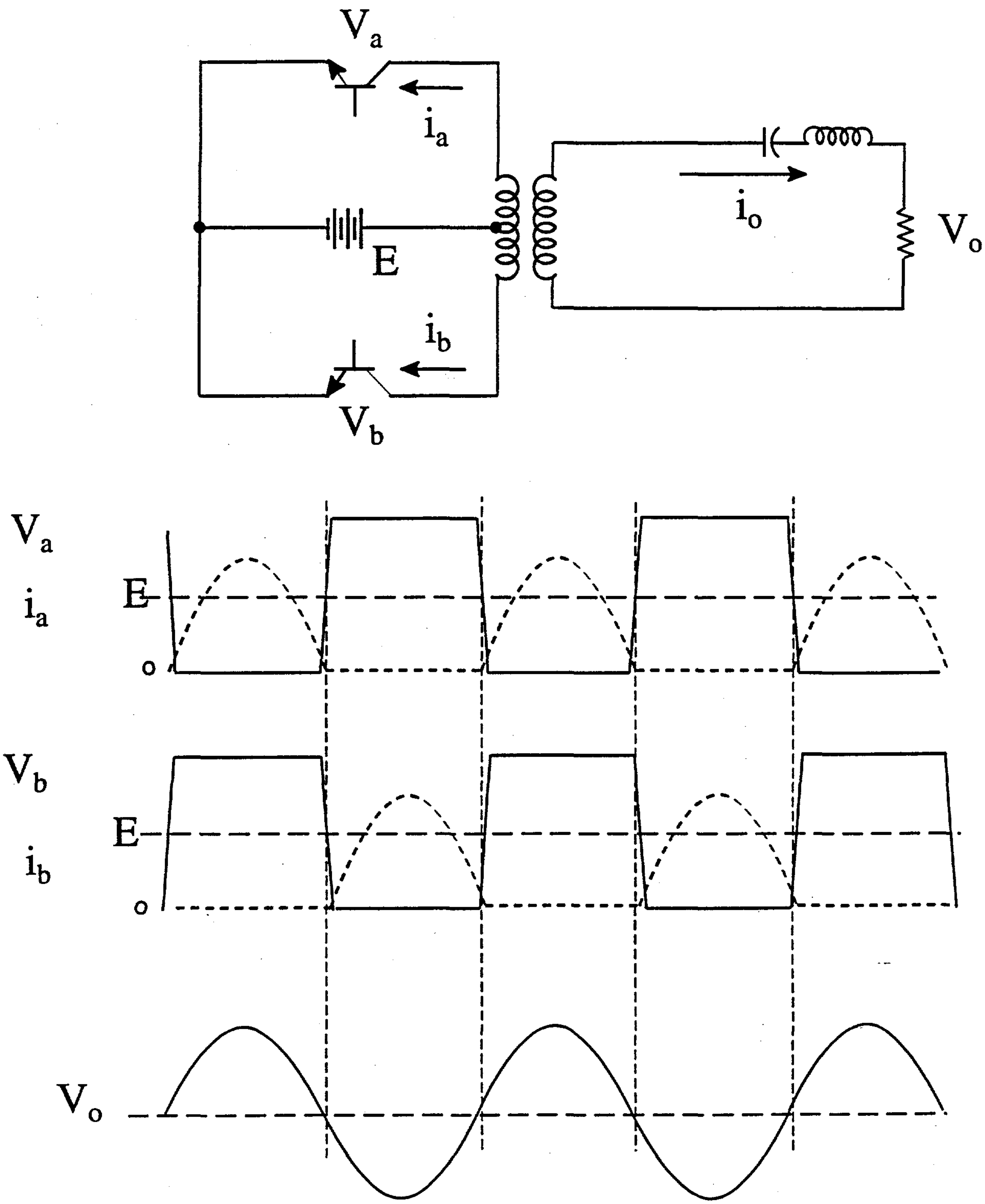
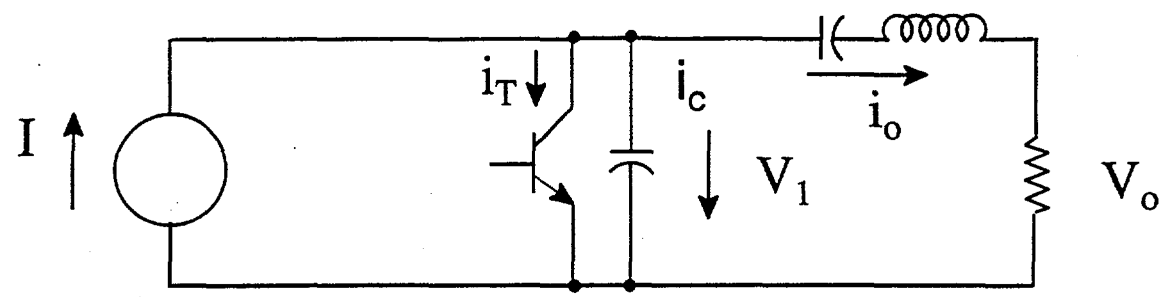


Figure B-2. Class D Operation -- Transformer Coupled



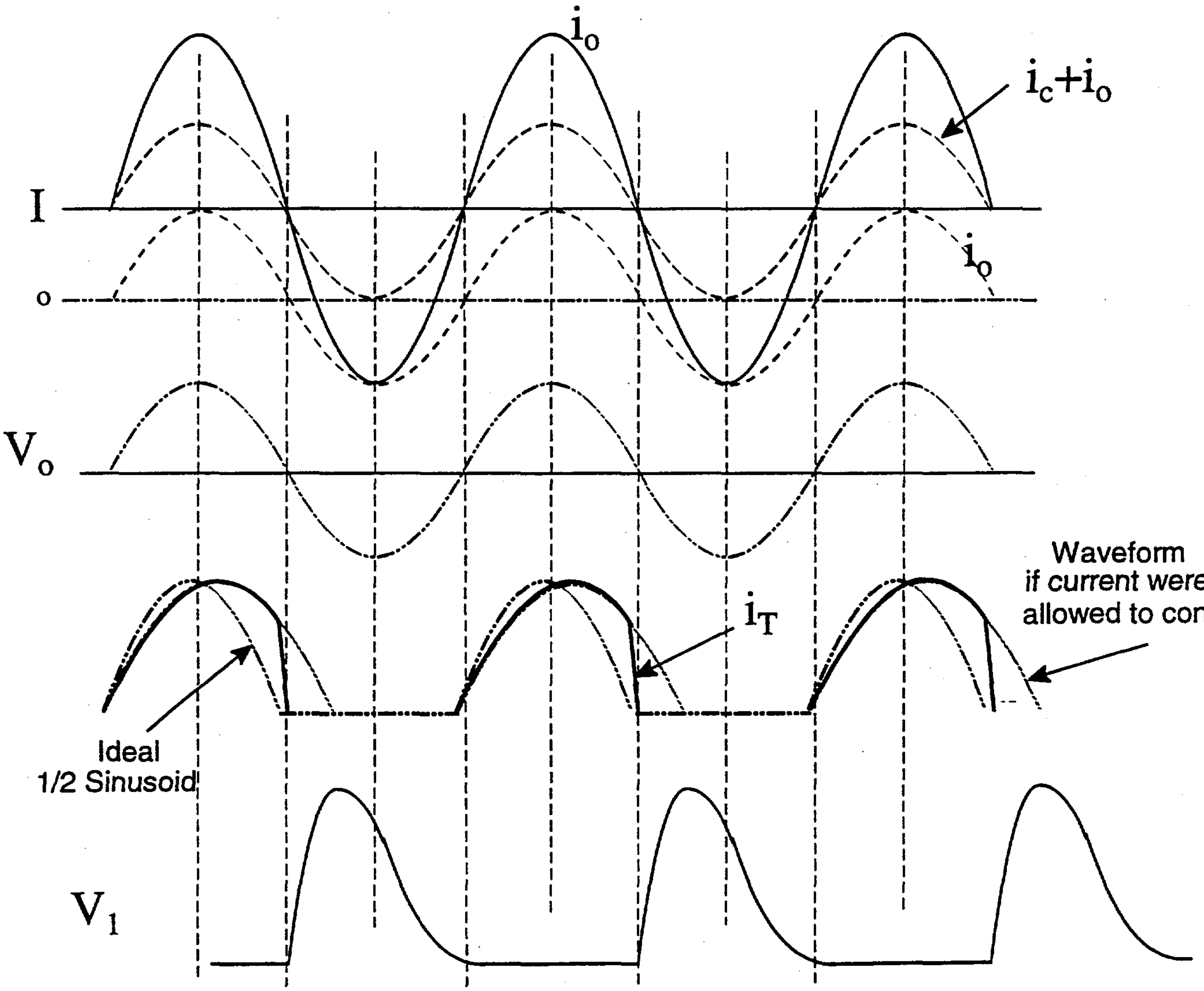
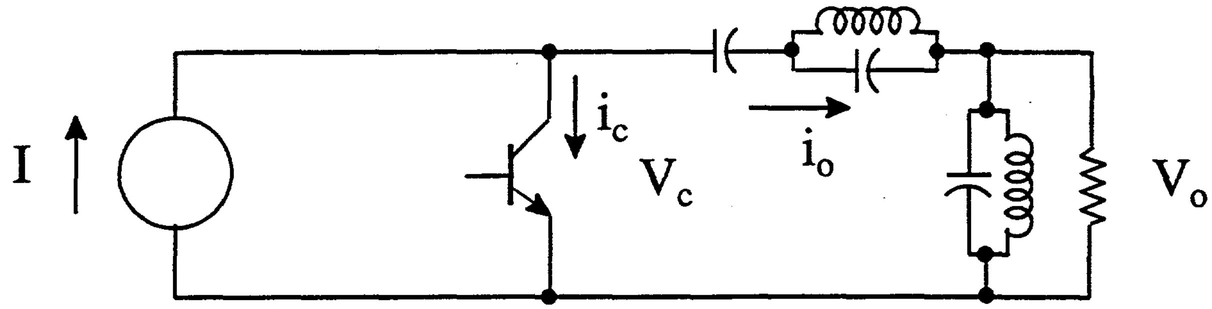


Figure B-3. Class E Operation



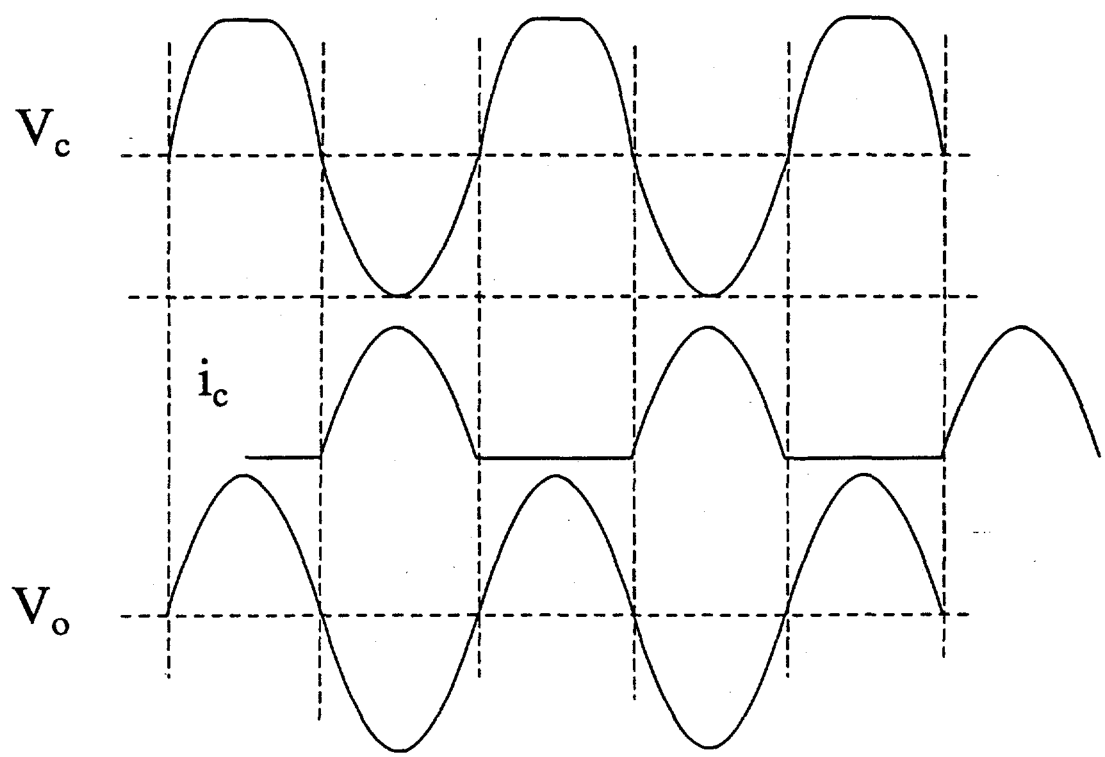


Figure B-4. Class F, or Class CD, or Single Ended Class D,
High Efficiency Class C, or Multiresonator

the DC source and storage capacitor voltage. Switching losses are low during transition times because current build up is limited by circuit inductance and not the impedance of the switching device itself. Class D operation is tolerant of reasonable load impedance changes. Class D circuits operate from voltage source supplies.

Class E - This mode differs from class D operation in that switch closure occurs at voltage zeroes rather than current zeroes. A key to successful class E operation is that the load resonant frequency and reactance to resistance ratio be such that the voltage returns to zero periodically. This is a critical requirement. Class E circuits are powered from a current source supply. Class E operation was dropped from consideration for this application because of very critical load sensitivity and the inability to achieve significant power added efficiency.

Class CD or F - This type of operation defines switch closure for less that one-half of the RF cycle period with switching occurring at neither circuit current or voltage zeroes. With switching transitions present, there are losses associated with the switching times.

This class of operation defines practical operation beginning with frequencies in the tens of MHz range. In general, switching times of a few nanoseconds preclude effective class D or class E operation beginning with this range and going upward.