USE OF A MAGNETRON AS A HIGH-GAIN, PHASED-LOCKED AMPLIFIER IN AN ELECTRONICALLY-STEERABLE PHASED ARRAY FOR WIRELESS POWER TRANSMISSION

M.C. Hatfield, University of Alaska Fairbanks
J.G. Hawkins, University of Alaska Fairbanks
W.C. Brown, Weston, MA

ABSTRACT. A conventional microwave oven magnetron is combined with a ferrite circulator to create a high-gain phase-locked amplifier with independent control of frequency and power output. The intended application is for electronically-steerable phased arrays for wireless power transmission.

INTRODUCTION

Many of the applications of microwave wireless power transmission (WPT) are dependent upon a high-powered electronically-steerable phased array composed of many radiating modules. The phase output from the high-gain amplifier in each module must be accurately controlled if the beam is to be properly steered. A highly reliable, rugged, and inexpensive design is essential for making WPT applications practical.

A conventional microwave oven magnetron may be combined with a ferrite circulator and other external circuitry to create such a system. By converting it into a two-terminal amplifier, the magnetron is capable of delivering at least 30 dB of power gain while remaining phase-locked to the input signal over a wide frequency range [1].

The use of the magnetron in this manner is referred to as an MDA (Magnetron Directional Amplifier). The schematic for the MDA and its interface with the drive signal are shown in Figure 1. This arrangement does not adversely affect the magnetron's 60% conversion efficiency of DC power into microwave power, nor does it affect the very low noise level of the microwave oven magnetron when operated in a continuous wave mode with the filament off.

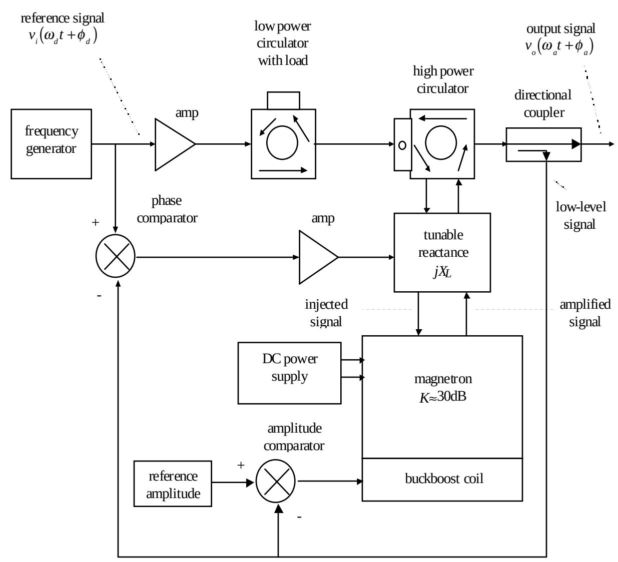

Figure 1. Schematic for the MDA

An amplified reference signal provides the low-level drive signal to the MDA. The reference signal source is protected by two microwave circulators, one acting solely as an isolator; the other as a signal router. If the input signal is strong enough to overcome the initial frequency separation, the magnetron will lock to the drive signal.

Phase-locking capability is provided by the reactance tuning components. A phase comparator measures the difference in phase between the reference and output signals. This difference is amplified and used to drive a servomotor controlling the position of a metallic tuning slug within the waveguide. This then changes the load seen by the magnetron, and therefore its operating frequency/phase. This closed-loop feedback system provides a high-gain, phase-locked amplifier operating over a wide frequency range.

For phased-array wireless power transmission, maintaining precise amplitude control is also essential. In such applications, it is likely that multiple MDA units must operate on a single power supply. Though not the focus of this paper, the "buckboost" coil is shown here for completeness.

The buckboost coil is an electromagnet that varies the total magnetic field strength within the magnetron. It provides a means to fix the output power at a desired level, independent of input voltage fluctuations. This approach allows multiple MDA units to be operated from a common voltage bus. For single units in a lab environment, the buckboost coil may be eliminated by using a current-regulated power supply.

THEORY OF OPERATION

The operation of the MDA can be explained with the aid of the expression for a frequency-locked oscillator [2].

$$\phi = \sin^{-1}\left[\frac{(f - f_0)Q_E}{f\sqrt{P_i/P_o}}\right]$$

where ϕ = phase shift between input and output of amplifier

f = free running frequency of the magnetron

f_0 = frequency of the drive source

P_i = power input from the driver

P_o = power out of the directional amplifier

Q_E = external Q of the magnetron

The phase shift between the input and output terminals of the frequency-locked oscillator is proportional to (1) the frequency difference between the locking signal and the free running oscillator, (2) the external Q of the device, and (3) the ratio of the output power to input locking power.

The frequency of the free-running oscillator can be changed to match that of the low-level drive by three methods: (1) internally change the resonant frequency of the magnetron by some mechanical or electronic tuning scheme, (2) take advantage of the change in frequency of oscillation as a function of current flow through the tube, or (3) change the reactance of the load into which the magnetron operates.

The first approach does not apply to the simple microwave oven magnetron, as it has no internal arrangement to vary its frequency. The second approach is applicable and has been pursued, but has the objection of also changing the output power of the magnetron.

The third approach best answers the needs of electronically-steerable phased arrays, because the frequency of operation and the output power can be independently controlled, while maintaining the necessary phase-lock conditions. Reactance tuning is accomplished by moving a small metallic obstruction along the centerline of the waveguide (see system description above). The change in load reactance is reflected back into the tube, thereby changing its operating frequency. The efficiency of this tuning arrangement is very high, as the power consumed represents only about 1% of the microwave output power.

PERFORMANCE

Once locked, the drive frequency input to the MDA can be varied over a wide range (15 MHz or more), with the amplitude of the output being independently controlled, as shown in Figure 2.

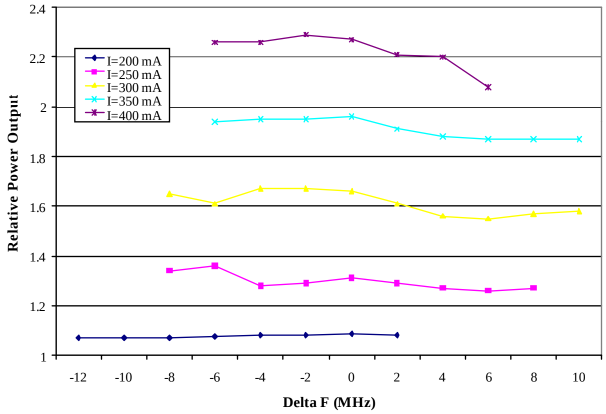

Figure 2. Power range and frequency range of MDA while operating phase-locked with 30 dB power gain with a matched load and no filament power. Power and frequency ranges are approximately independent.

The peak-to-peak phase error as a function of drive frequency is shown in Figure 3. The feedback loop keeps the phase shift within $\pm 5^0$ while operating over a wide frequency range.

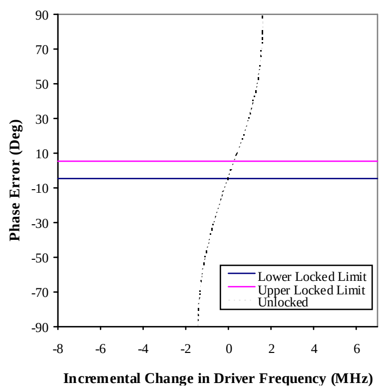

Figure 3. Peak-to-peak phase error limits of the phase-locked MDA compared with an ordinary frequency-locked (not phase-locked) magnetron. Frequency-lock in this case is due to injected signal only, without the use of load reactance tuning.

OPTIMIZATION

Continuation of early work in this field [1] has resulted in a number of sensitivity analyses. One concern in designing a practical WPT system is the transition of the MDA from its open-loop to closed-loop operation.

Based upon a resonant cavity-type oscillator, the MDA (in its open-loop mode) has an output dependent upon the load seen by the magnetron. The size of the tuning element used and its position along the waveguide can greatly affect the frequency and power output from the magnetron, as shown in Figures 4 and 6.

The amount of frequency fluctuation provided by a tuning slug is directly proportional to its size:

Slug	Size
1	5/8” DIA x ¼”
2	5/8” x ½”
3	5/8” x ¾”

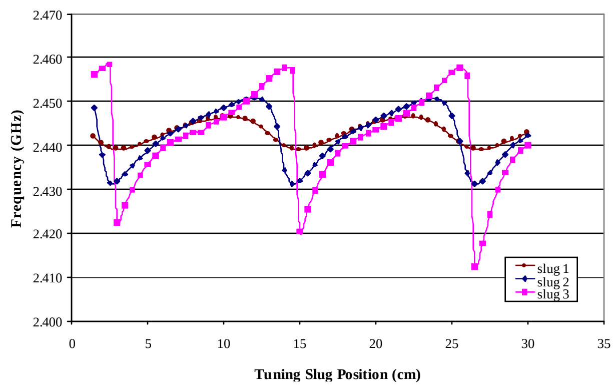

Figure 4. Effects of Tuning Slug Sizes and Locations on Magnetron Operating Frequency. Data was collected with a matched load and the magnetron filament off. The steep sloped areas occur along the “sink” of the Rieke diagram. The resistive component of the load and therefore operating efficiency remain nearly constant over the entire tuning range.

Increasing the size of the tuning slug shifts the locations of frequency maxima/minima closer together, eventually creating a discontinuity between them. Large tuning slugs "pull" this discontinuity away from the location of the center frequency crossing of the smaller tuning slugs. Sufficiently large slugs create a pronounced hysteresis effect, yielding different frequency crossover locations depending upon the direction of approach, as shown in Figure 5 (Figure 4 data taken left-to-right).

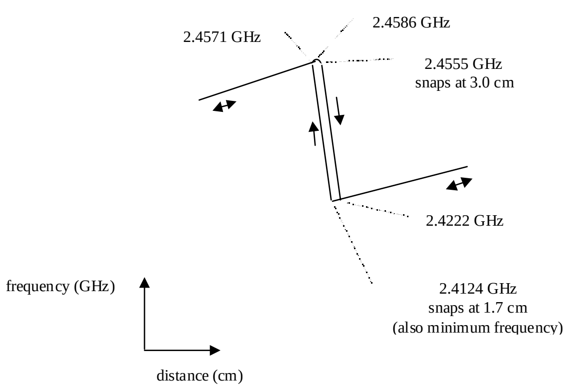

Figure 5. Hysteresis loop for 5/8" DIA x ¾" tuning slug, Samsung model 2M181.

Additionally, the slope of the "steep" frequency regions tend to lessen nearer to the magnetron (magnetron located just past 30 cm on the charts). For some tuning slugs, this slope change can be significant and can determine whether that size slug may be used.

The power transfer efficiency provided by a tuning slug is also proportional to its size:

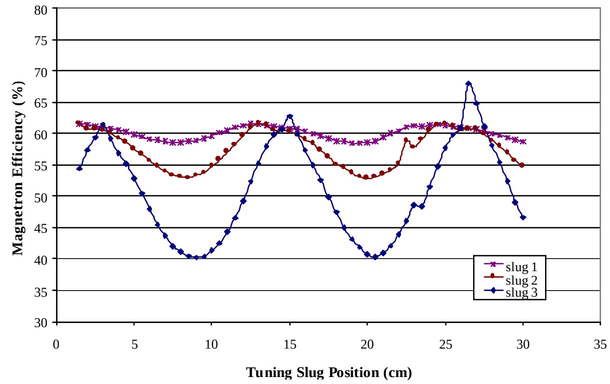

Figure 6. Effects of Tuning Slug Sizes and Locations on Magnetron Power Efficiency. Efficiency without a tuning slug is 60%.

Larger tuning slugs provide greater efficiencies in the steep regions of the frequency curves, but on the average provide less efficiency. Regions of high power transmission efficiency correlate with the "steep" frequency transition regions. These same regions, as expected, also correlate to regions of lower magnetron case temperatures.

SUMMARY

The MDA operation has been successfully demonstrated in a development supported by the NASA Center for Space Power at Texas A&M University [1] and that is now undergoing further study and refinement at the University of Alaska Fairbanks. The long range objective of this development is to combine the MDA with a section of slotted waveguide array to form one radiation module of an electronically-steerable phased array for wireless power transmission.

REFERENCES

[1] W.C. Brown, "Magnetron Directional Amplifier Development" Final Report 1994, Texas A&M Research Foundation, Subgrant No L300060, Prime Grant No NAGW-11194, Project RF-250095

[2] E.E. David, "Phasing of RF Signals" in Okress, Crossed Field Microwave Devices, Vol 2, Academic Press, 1961

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