THE SOPHISTICATED PROPERTIES OF THE MICROWAVE OVEN MAGNETRON

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ABSTRACT

The magnetron commonly used in the microwave oven has unusually low noise and long life resulting from an internal feedback process that limits the emission from the cathode to optimum values for these properties. Without compromising these properties the magnetron can be combined with external circuitry to lock the output phase to the input phase and simultaneously provide 30 dB of gain. Together with its low cost and universal availability, these properties make it an attractive option for a number of applications.

INTRODUCTION

It is well known that the magnetron which supplies 700 watts of average power to the ubiquitous microwave oven is made in an amazingly large quantity of 15,000,000 annually, and at an amazingly low price of less than $15.00 It is also well known for its high conversion efficiency of 70% and small size and mass. What is not generally known and what this paper seeks to briefly describe are its amazingly low noise and long life properties, and how it can be combined wih external circuitry to convert it into a phase-locked amplifier with 30 dB gain, without compromising its noise or life properties. Such amplifiers are ideal for combining with slotted waveguide radiators to form radiating modules in a low-cost, electronically steerable phased array for beamed power transmission purposes. Conceivably there are other applications.

The low noise and long life properties are associated with a feedback mechanism internal to the magnetron that holds the emission capabilities of the cathode to those levels consistent with both low noise and long life. This internal feedback mechanism is effective when the magnetron is operated from a relatively well filtered DC power supply with the cathode heated by back bombardment power alone. The external power supply that heats the filament is removed after starting the tube. These are not the conditions under which the tube is operated in the microwave oven and where the noise levels may be 60 to 100 dB higher. The low noise in the magnetron persists over a very broad range of operating parameters and is independent of whether it is operated as an oscillator or an amplifier.

The basic amplifier configuration is that of a "reflection amplifier" as depicted in Figure 1, where the drive power injected through a ferrite circulator cannot be distinguished from the power reflected from a mismatched load. The principle, however, can be used at two different levels. The common use is to operate the reflection amplifier without tuning the free running frequency of the magnetron to the frequency of the driver. Under those circumstances there will be a phase difference between the input and the output of the device and it will be limited in practical values of gain.

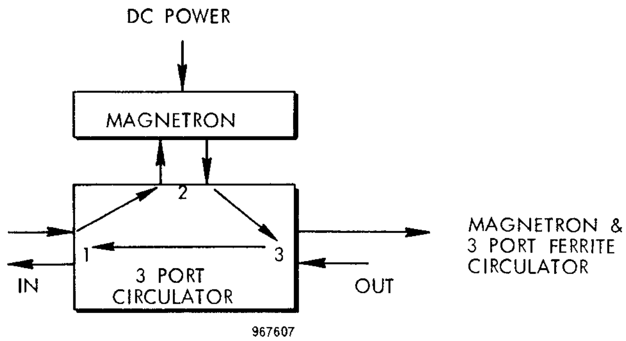


Fig. 1 Circuit schematic for the magnetron directional amplifier - a reflection type amplifier.

The more sophisticated level of operation is to use the phase difference between input and output to retune the magnetron to operate at the same frequency of the driver,and thereby not only preserve the phase but also allow practical operation at gain levels of 30 dB or even greater.

The tuning can be accomplished by mechanically tuning the tube, or more practically, by taking advantage of the magnetron's frequency dependency upon the value of anode current, "magnetron pushing," or reactive component of load "magnetron pulling." Most of the experimental work has made use of changing the anode current.

The subject matter to be reported upon is well documented in a large number of NASA supported studies that are noted in the references.(1,2,3,4,5)

LOW NOISE GENERATION

Noise data were taken with the magnetron in combination with a ferrite circulator, operated as a reflection amplifier but referred to more specifically in the referenced literature as a "magnetron directional amplifier," as shown in Figure 1 (Sec. 4 of reference 1). The tubes external filament supply was removed after the start up; a portion of the output of a microwave oven magnetron operating in a purely oscillating mode was used as the drive source. Noise levels were observed on a spectrum analyzer and sensitivity was enhanced by putting the output through a 24 dB narrow notch filter (4 dB at ± 2 MHz) to suppress the carrier relative to the noise measurements.

With such an arrangement the noise in a frequency band of 300 KHz at 10 MHz from the carrier was more than 103 dB below the carrier level, limited by the sensitivity of the noise measuring set up. Noise levels in a 300 KHz bandwidth were consistently 100 dB below the carrier over a broad range of current, operating voltage, magnetic field, load, and gain. A typical presentation of noise level versus input microwave drive level is shown in Figure 2. With 0.6 watt drive the gain of the amplifer at the 560 watts output level was approximately 30 dB. There appears to be no increase in noise at that gain, nor would it be expected because input drive at that level represents only a small perturbation of the tubes undriven (oscillator) behavior. Operating at this gain level, however, is not practical without the addition of phase locking loops to be discussed later.

Measurements of phase noise close to the carrier were also made with other test arrangements (pp 4-8 to 4-13 of Ref. 1). The noise in a 1 KHz band removed 10 KHz from the carrier was 110 dB below the carrier level. Thus the tube has acceptable noise levels for some types of communication services.

SELF REGULATION OF FILAMENT TEMPERATURE TO MINIMIZE NOISE AND MAXIMIZE LONG LIFE

The low noise in the microwave oven magnetron is associated with keeping the temperature of the cathode in a temperature limited emission condition, as contrasted to a space charge limited condition considered essential for low noise operation in other common microwave devices such as the klystron and traveling wave tube. Because evaporation of electron emitting material from the cathode is greatly accelerated with an increase in temperature, the temperature limited condition of the cathode is also the desired condition for maximum tube life. The relationship of low noise to the temperature limited emission was established with the aid of an optical pyrometer to observe the temperature of the purely primary emitting cathode. Readings of cathode temperature versus anode current were made and the resulting relationship closely followed the Richardson-Dushman equation for temperature limited emission as shown in Figure 3 (Section 5 of Ref. 1).

The data of Figure 3 implies some form of negative feedback control which has been characterized and formalized in Figure 4 in terms of data taken external to the tube. The components of the feedback loop shown in Figure 4 have been quantified in unpublished material.

An examination of Figure 3 indicates that there is more emission of current than called for by the strict adherence of the cathode temperature and corresponding emission to the Richardson-Dushman equation, suggesting that there is some excess emission which would normally be difficult to substantiate and measure. However, the thermal inertia of the carburized thoriated tungsten cathode makes it possible to evaluate the excess emission by changing the operating voltage level instantaneously. Any excess emission is then revealed as an instant increase in anode current whereas the ultimate anode current will depend upon the back bombardment process to heat the cathode to a higher temperature. The transient behavior, as shown on a CRT for example, is depicted by the insert in Figure 5. Figure 5 shows how the magnitude of the excess emission varies with the anode current, and also its ratio to the value of anode current.

The impact of the addition of external heater power upon the excess emission was also evaluated. It was found that a reduction in back bombardment power compensated to within 5% of the added heater power, indicating a gain in the internal negative feedback loop of about 20. The

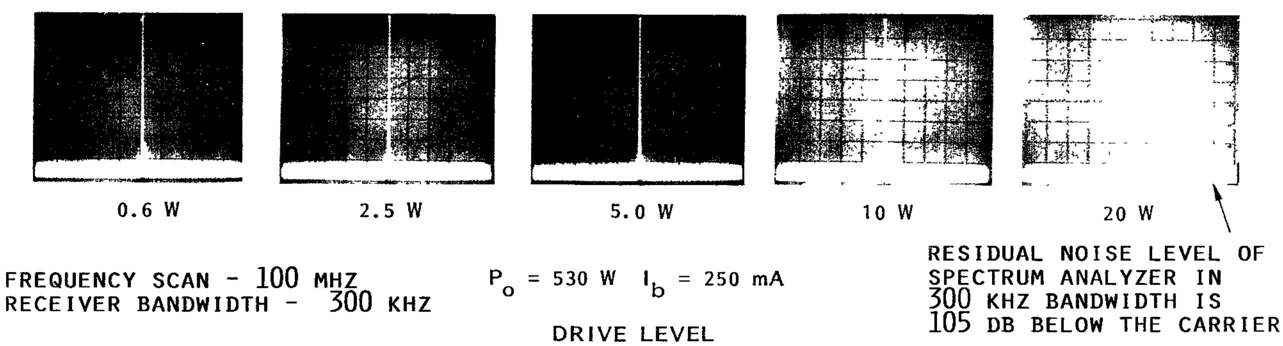


Fig. 2 Spectrum quality as a function of rf drive or gain. Spectrum at an input level of 0.6 watts with an output of 530 watts represents a gain of approximately 30 dB. Noise level for the gain remains unchanged from level at 14 dB gain.

external heater power may be regarded as an external perturbation imposed upon the feedback loop.

As the external heater power was increased to about one third of its normal value, the excess emission became large enough to trigger switching to a noisy operating mode which probably is related to a rearrangement of the space charge in a fundamental way about the cathode.

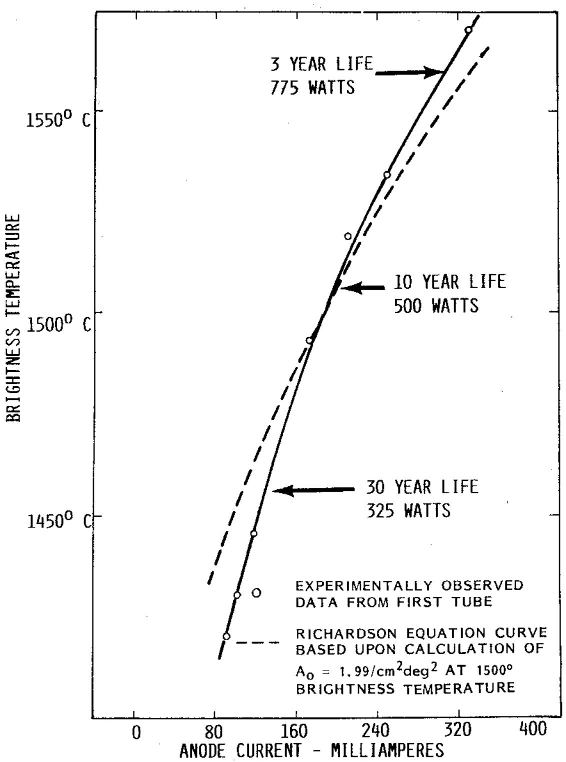


Fig. 3 Observed relationship between anode current and filament temperature closely follows that of Richardson-Dushman equation for temperature limited emission.

OPERATION OF THE MAGNETRON AS A HIGH GAIN, PHASE LOCKED AMPLIFIER

The behavior of the magnetron when power is injected into it through a ferrite circulator can be examined with the aid of the following well-known relationship for a reflection amplifier

$$\Theta = \sin^{-1} \frac{\Delta f_o Q_e}{f_o \sqrt{\frac{P_{in}}{P_o}}}$$

Θ is the phase shift between input and output of the amplifier

Δf_o is the difference between the frequency of the drive source and the frequency of the magnetron if it were permitted to run freely

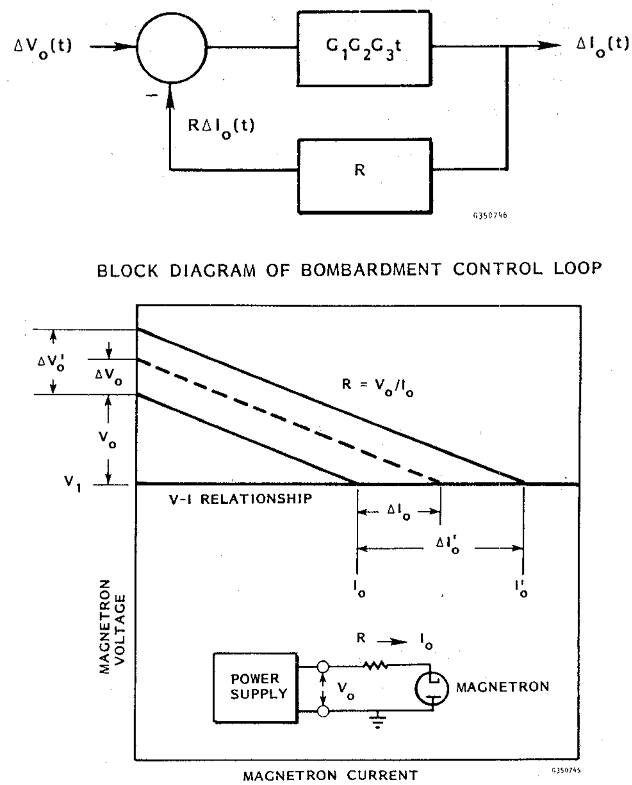
Q_e is the external Q of the magnetron

P_i is the power level of the microwave drive source

P_o is the microwave power output of the amplifier

The phase shift is limited to ± 90°. If the argument of the inverse sine exceeds unity the magnetron will unlock from the drive frequency.

Most reflection amplifiers operate in the mode which requires no feedback circuitry. However, if a phase comparator is used to compare the phases of the input and output as shown in Figure 6 and the error signal used to energize a feedback loop to return the magnetron to the frequency of the drive signal, the argument of the [illegible]



DEFINITION OF COMPONENTS OF FEEDBACK CONTROL LOOP

Fig. 4 Control theory format for the transient and steady state behavior of the magnetron.

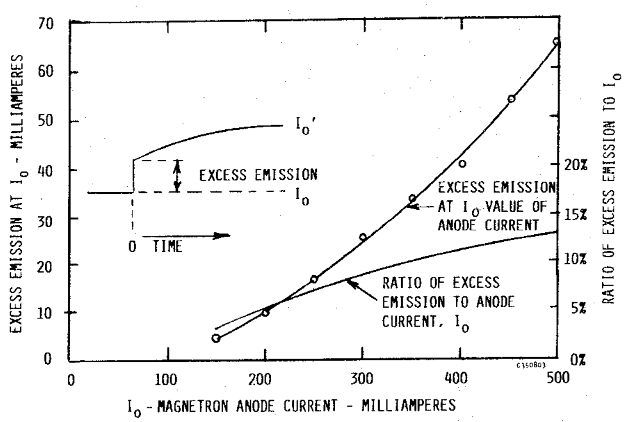


Fig. 5 Observed excess current as a function of anode current.

sine is kept close to zero even in the presence of very high rations of Po to Pi.

The tuning approach that was used was to vary the anode current which changes the free running frequency of the magnetron. The current is changed by changing the magnetic field which increases or reduces the operating voltage level, and therefore the anode current intercept of the load line with a fixed voltage power supply as suggested by Figure 4. The magnetic field was changed by a small "buck-boost" coil inserted into the magnetic circuit as shown in Figure 7. The coil operates with a few watts input, usually less than five, from an operational amplifier that amplifies the phase error signal.

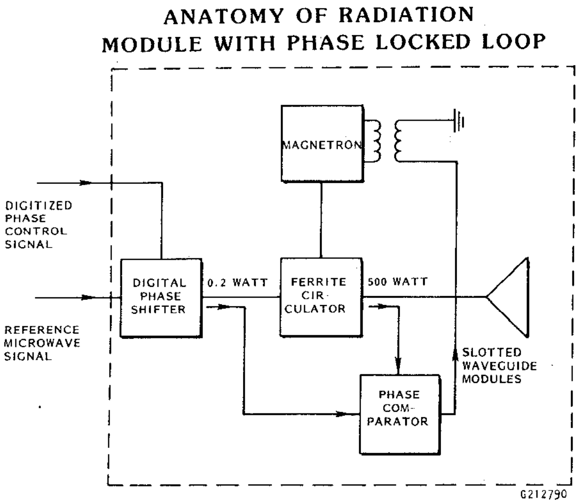


Fig. 6 Circuit for phase-locked, high-gain magnetron directional amplifier. Diagram also shows its application to a radiating module in an electronically steerable array antenna.

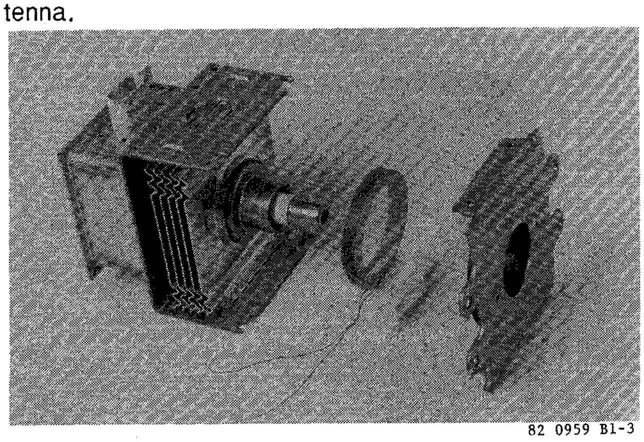


Fig. 7 Implementation of phase-locked, high gain circuitry with addition of buckboost coil to microwave oven magnetron.

A comparison of the behavior of the high-gain, phase-locked amplifier is shown in Figure 8 with the magnetron directional amplifier in Figure 1. Where the objective is to maximize the ratio of drive frequency range to phase shift variation over that range, an improvement factor of 70 is indicated in Figure 8. But, perhaps more importantly, any variation in the magnetron free running frequency caused by change in the anode temeprature, anode current, life, etc., may amount to considerably more than 2.5 MHz, the maximum locked frequency range of the conventional reflection amplifier at a 30 dB gain level.

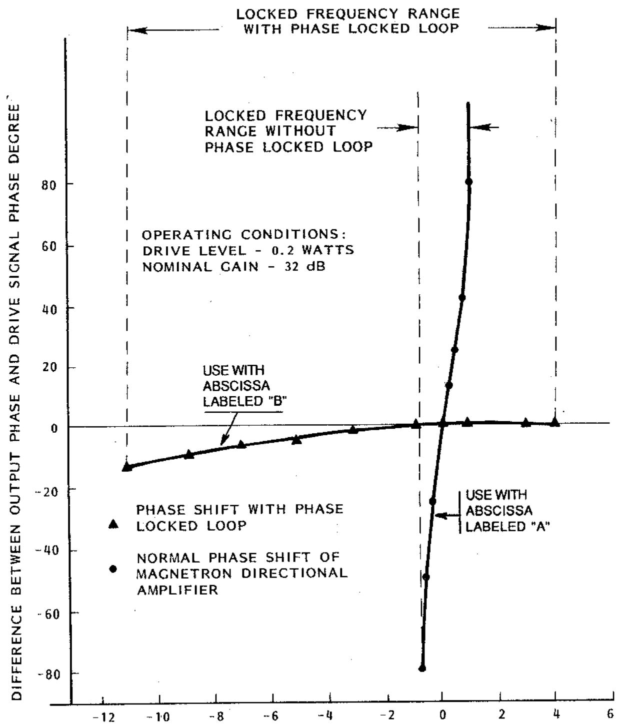


Fig. 8 A. DIFFERENCE BETWEEN FREQUENCY OF DRIVE A AND FREE RUNNING FREQUENCY OF MAGNETRON FOR THE CONVENTIONAL FREQUENCY LOCKED MAGNETRON DIRECTIONAL AMPLIFIER

B. CHANGE IN DRIVE FREQUENCY FOR PHASE LOCKED MAGNETRON DIRECTIONAL AMPLIFIER IN WHICH MAGNETRON FREE RUNNING FREQUENCY IS TUNED TO THE FREQUENCY OF THE DRIVER

ACKNOWLEDGEMENT

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