The Magnetron — A Low Noise, Long Life Amplifier

This author, a leading proponent of the transmission of power via microwave beams, describes how the common microwave oven magnetron can be externally locked to provide 30 dB of gain – resulting in a 500 watt, 70% efficient, $15, coherent microwave source.

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The 2450 MHz magnetron which supplies 700 watts of average power to the ubiquitous microwave oven is made in a quantity of 15,000,000 units annually at a very low price, less than $15. It has a high conversion efficiency of 70% and small size and mass. What is not generally recognized is that it has very low noise and long life properties, and that it can be combined with 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, which motivated this study. However, there are conceivably numerous other practical purposes for which these properties can be utilized.

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 under which the noise levels may be 60 to 100dB higher. The low noise in the magnetron persists over a very broad range of operating parameters, 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 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.

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 30dB or even greater.

The tuning can be accomplished by mechanically tuning the tube, or more practically, by taking advantage of the magnetron's frequency dependence 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 [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 literature as a "magnetron directional amplifier", as shown in Figure 1 [1, Sec. 4]. The tube's 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.

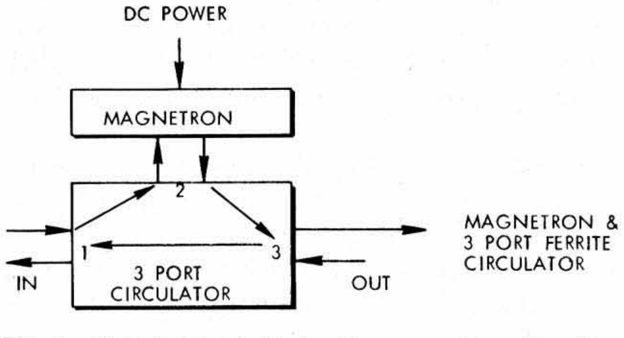


Fig. 1 Circuit schematic for the magnetron directional amplifier – a reflection type amplifier.

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 band- width 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 amplifier 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 to the tube's 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 [1]. The noise in a 1 KHz band removed to 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 for low noise, 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 travelling 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

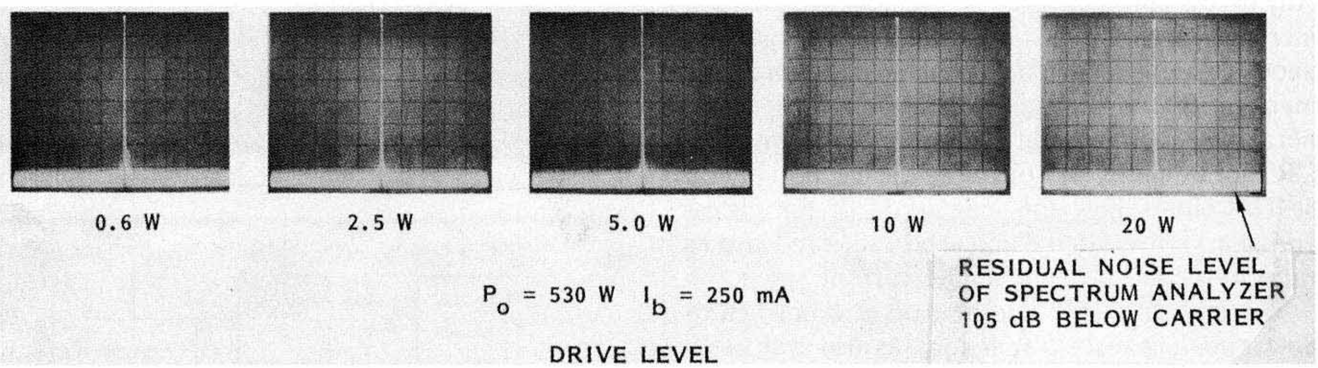


Figure 2. Spectrum quality as a function of rf drive or gain. Spectrum at an input level of 0.6 watts with an output of 530 watts represents a gain of approximately 30 dB. Noise level for the gain remains unchanged from level at 14 dB gain.

the cathode temperature versus anode current were made and the resulting relationship followed the Richardson-Dushman equation for temperature limited emission as shown in Figure 3 [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 he 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 instantaneously.

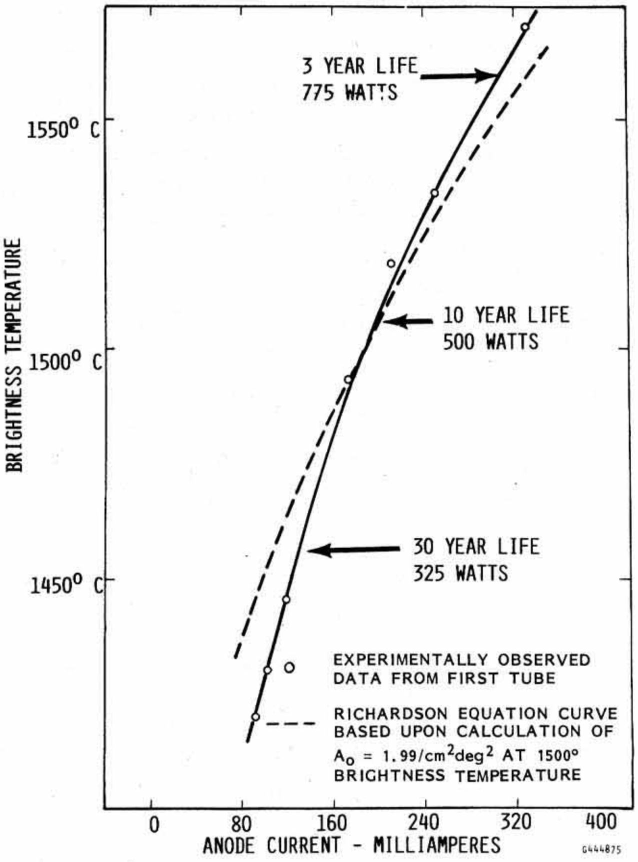
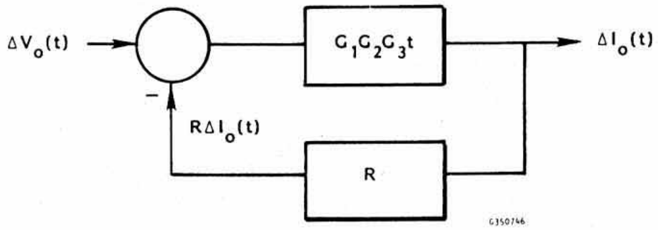
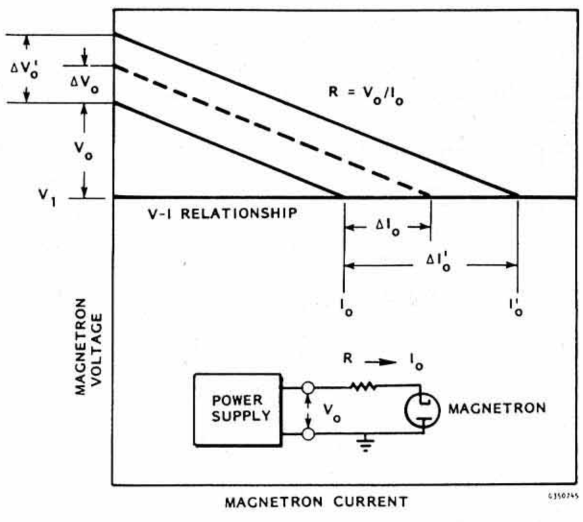


Fig. 3 Observed relationship between anode current and filament temperature closely follows that of Richardson-Dushman equation for temperature limited emission.



BLOCK DIAGRAM OF BOMBARDMENT CONTROL LOOP



DEFINITION OF COMPONENTS OF FEEDBACK CONTROL LOOP

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

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. This shows how the magnitude of the excess emission varies with the anode current,, and also its ratio to the value of the 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 external heater power may be regarded as an external perturbation imposed upon the feedback loop.

As the external heater power was increased by 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.

Operation 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 using the relationship for a reflection amplifier given in Table I.

The phase shift is limited to + 90 degrees. 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 inverse sine is kept close to zero even in the presence of very high ratios of Po to Pi.

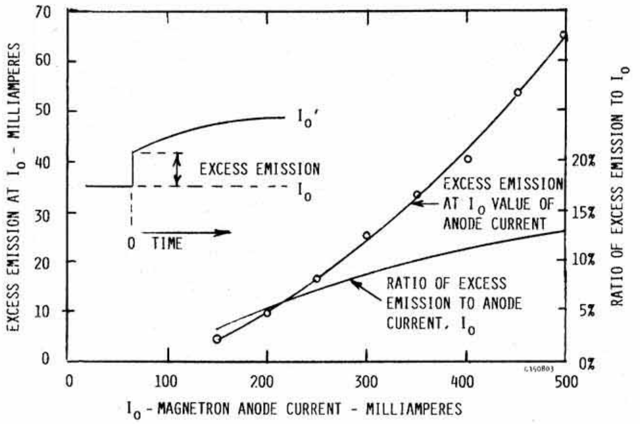


Figure 5. Observed excess current as a function of the anode current.

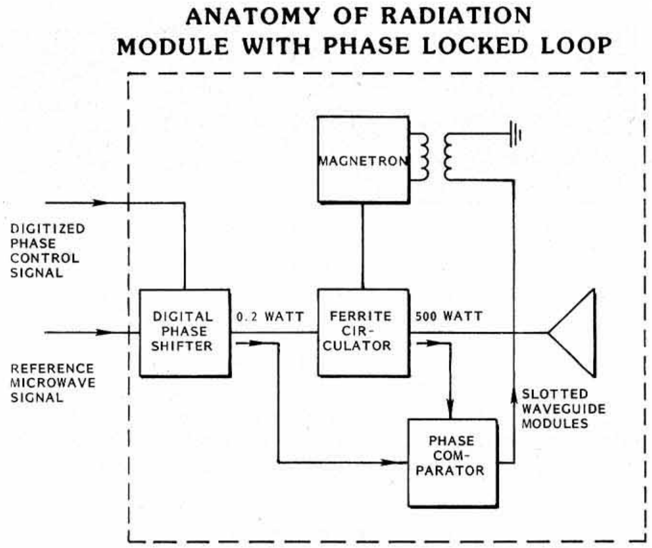


Fig. 6 Circuit for phase-locked, high-gain magnetron directional amplifier. The diagram also shows its application to a radiating module in an electronically steerable array antenna.

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.

A comparison of the behavior of the high-gain, phase-locked amplifier is shown in Figure 8 with the magnetron directional amplifier described in Figure 1. Where the objective is to maximize the

$$\Theta = \mathrm{SIN}^{-1}\ \frac{\Delta f_o\, Q_e}{f_o\sqrt{P_i/P_o}} \quad \text{(Ref. 5)}$$

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
Qe	is the external Q of the magnetron
Pi	is the power level of the microwave drive source
P_o	is the microwave power output of the amplifier

Table I. Feedback amplifier relationship.

ratio of drive frequency range to phase shift variation over that range, an improvement factor of 70 indicated in Figure 8. But, perhaps more importantly, any variation in the magnetron free running frequency caused by change in the anode temperature, 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.

Acknowledgements

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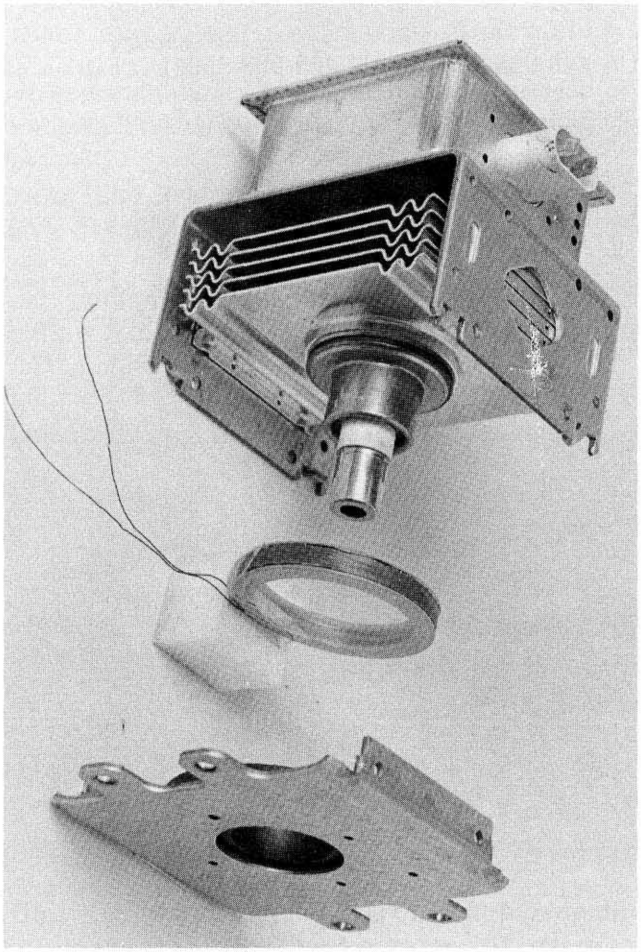

Fig. 7 Implementation of phase-locked, high-gain, circuitry with addition of buckboost coil to microwave oven magnetron.

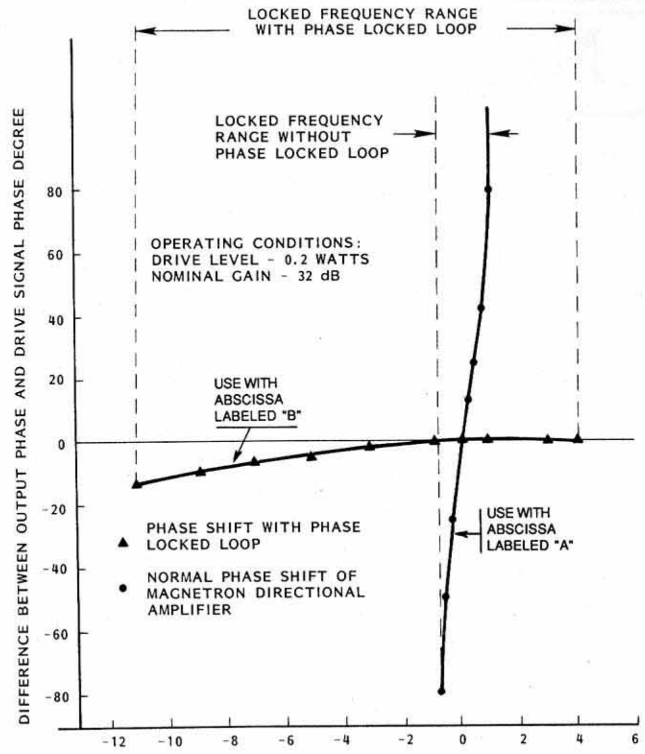

Figure 8. A) Difference between frequency of Drive A and free running frequency of magnetron for the conventional frequency locked magnetron directional amplifier and B) Chang in drive frequency for phase locked magnetron directional amplifier in which magnetron free running frequency is tuned to the frequency of the driver.

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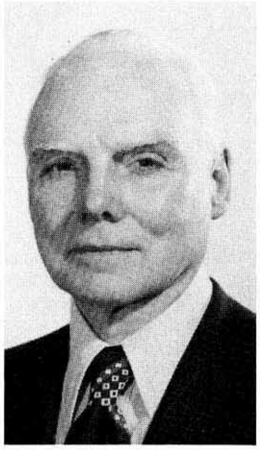

William C. Brown *received his electrical engineering education at Iowa State University and at Massachusetts Institute of Technology, Cambridge, Mass. He was with the Raytheon Company until his retirement in 1984.*

His technical contributions while at Raytheon were in the areas of crossed-field microwave tubes and their applications, which included the first demonstration of the use of a microwave beam to sustain a microwave powered aircraft.

In recent years Mr. Brown has been a proponent of and a participant in the technological development and use of power transmission via microwave beams, with emphasis on its space applications.