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A HIGH-POWER, 13-CM MAGNETRON TRANSMITTER

Here's a new use for your microwave oven's magnetron

The greatest obstacle to overcome in working moon bounce (EME) or tropospheric scatter (tropo) in the 13-cm band lies in generating the RF power required. Very few devices are available to the radio Amateur which can be used to build a high power transmitter. But I've found one that's capable of delivering high power (500 to 1000 watts of RF output) and is inexpensive ($50 to $75). Some of these devices even operate at the upper end of the 13-cm ham band. I'm referring to the microwave-oven magnetron.

I wanted to investigate the feasibility of designing a low-cost, high-power transmitter for the 13-cm band using a microwave oven magnetron in the injection-locked configuration. After some investigation, I designed and built the 1-kW, 13-cm oven-magnetron transmitter described here.

Magnetron characteristics

A magnetron is a single port device to which the load is connected. Any change in the reactance component of the load changes the frequency of the free-running magnetron. **Figure 1** is a typical load diagram showing how the frequency varies with changes in magnetron loading. The center of the diagram corresponds to the matched condition, where no reflection occurs. As

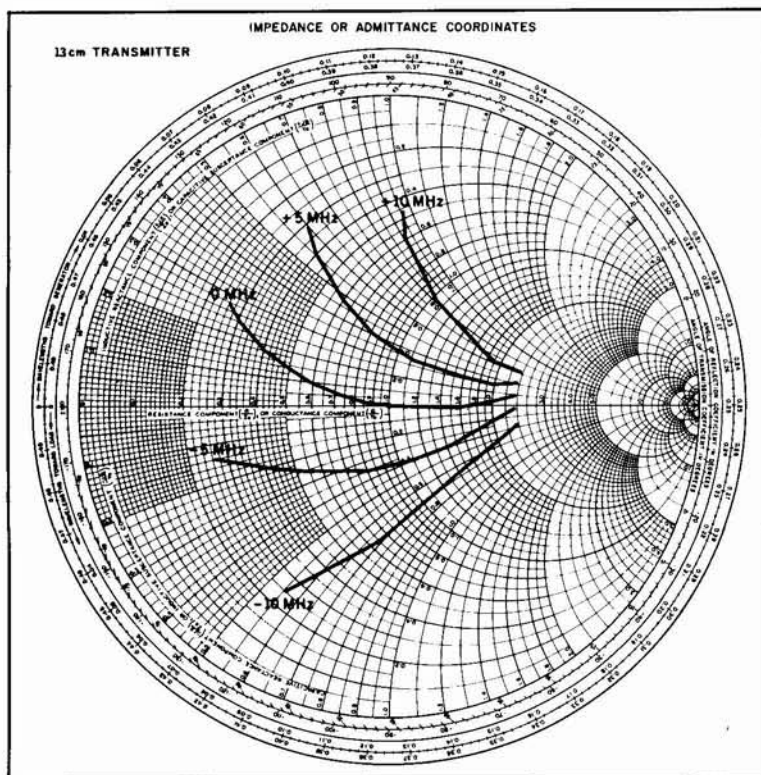the reactive component of the load changes, the frequency changes accordingly. Because

Figure 1. Magnetron load diagram.

the magnetron can't distinguish between reflected power from a passive load and power injected into it from some other source, it's possible to lock the free-running magnetron to a stable source.

To inject an external signal source into the magnetron, it's necessary to connect a circulator between the magnetron and the load, as shown in **Figure 2**. The amount of power required to lock the magnetron is derived from:[1]

$$\sqrt{P1/P} > Qe \, |\Delta fo/fo| \qquad (1)$$

where P1 is the injection power, P is the magnetron output power, Qe is the loaded Q of the magnetron, Fo and ΔFo are the frequency and frequency deviation in MHz.

The amount of power required to injection lock a typical oven magnetron at Fo = 2448 MHz, Qe = 20, P = 750 watts, and a locking range of 20 MHz, so Fo = 10 MHz, is:
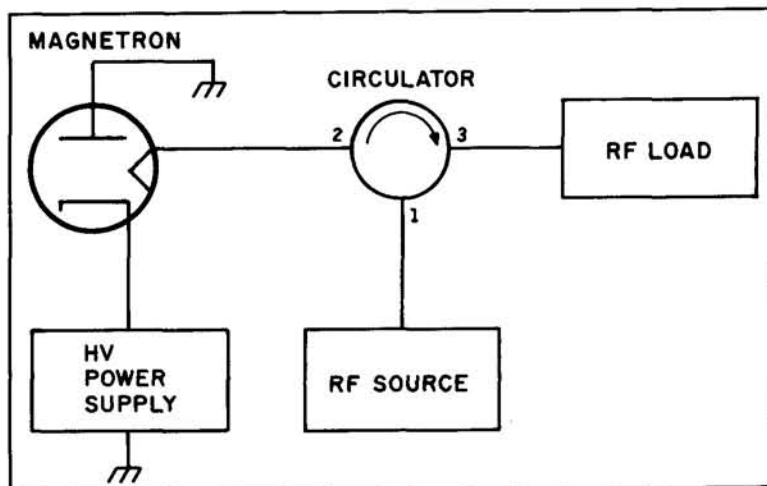
$$\sqrt{P1/750} > 20 \times 10/2448 = 0.082$$
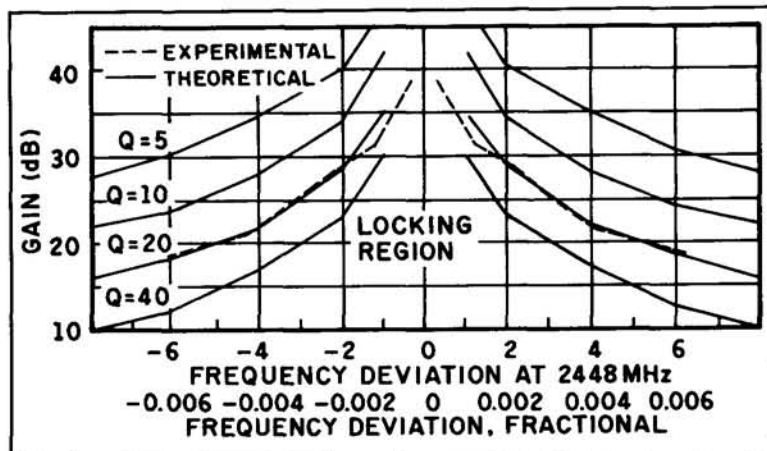

Figure 2. Injection-locked magnetron, block diagram.

Figure 3. Theoretical locking range of magnetron and experimental data.

or

$$P1 = 5.0 \; watts$$

In practice, approximately 10 watts would be used to overcome circuit losses, giving a gain of almost 19 dB.

Plots of **Equation 1** are shown in **Figure 3** for four values of Qe, along with an actual plot of an oven magnetron. As you can see, the experimental data are close to theoretical.

Frequency response

For complete information, it's necessary to determine how fast the magnetron will respond to variations in the injection frequency. The data in **Figure 3** are based on static conditions of the magnetron and do not indicate its ability to follow high-frequency modulation. The pull-in is complete when:

$$t = Qe/Fo \, \sqrt{P/P1} \qquad (2)$$

where t is in μsec, if Fo is in MHz.[2] For the previous example, the pull-in time is about 0.07 μsec. This is the time required to swing across the lock-in range. It represents one-half Hz of the modulation. Thus, the maximum modulation frequency is about 7 MHz. The modulation will normally be restricted to less than the full lock-in range, so **Equation 2** becomes

$$F = Fo/2Qe \, \sqrt{P1/P} \qquad (3)$$

where F in MHz is the maximum modulation frequency and Fo is in MHz.

This means the injection-locked magnetron can be used at any modulation frequency desired, including ATV.

Automatic frequency control

The magnetron will remain locked to the injection source frequency as long as the phase difference doesn't vary more than 90 degrees. This limit may be exceeded if there's power-supply drift and/or thermal drift of the magnets on the magnetron. To prevent the magnetron from dropping out of lock, you could use a phase-sensitive detector to monitor injection signal versus output signal. The phase detector output could then control the magnetron cathode current and maintain lock to within a few degrees.

Safety first

Before discussing the transmitter, I'd like to take note of some safety precautions.

High Voltage

The high voltages used in this transmitter are in the *lethal* range. Great care must be taken when testing, troubleshooting, and operating this type of transmitter. The voltages used are somewhat higher than those in common Amateur high-power amplifiers. Because the magnetron anode is operated at ground potential, the filament circuit is at a very high negative potential. Most high-power Amateur amplifiers have the anode at high voltage and the filament at near ground potential. It's very important not to forget this fact. *Negative voltage will kill just as quickly as positive voltage.*

High RF radiation

The RF power output of this transmitter is at the same level as that developed in the usual Amateur high-power amplifier. However, the chance for exposure to dangerous RF radiation is much greater at 13 cm. A 2-1/2 × 1/64-inch gap in the side panel of an HF power amplifier will let little radiation escape. But this same size gap in a 13-cm transmitter forms a 1/2-wavelength slot antenna, which has the potential to radiate the full power of the transmitter. This could be 250 watts/per square centimeter, or 250,000 times the radiation level I consider safe at this frequency.

The 13-cm transmitter design

The 13-cm transmitter (**Photo A**) consists of four major sections: the RF deck, 13-cm transverter, constant-current regulator, and magnetron HV power supply.

Figure 4 shows the block diagram of the transmitter. The RF output of the magnetron is fed to the transmit port of a three-
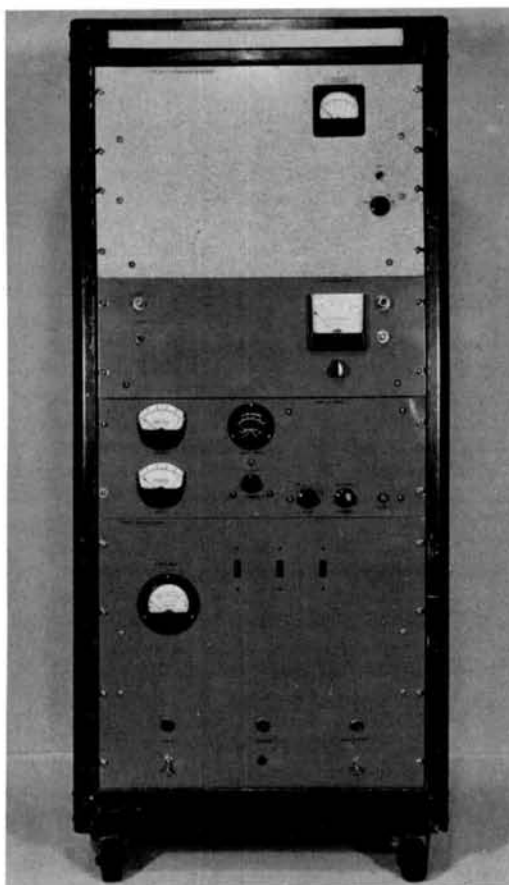

Photo A. 13-cm oven-magnetron transmitter. Top to bottom: RF deck, 13-cm transverter, constant-current regulator, and HV power supply.
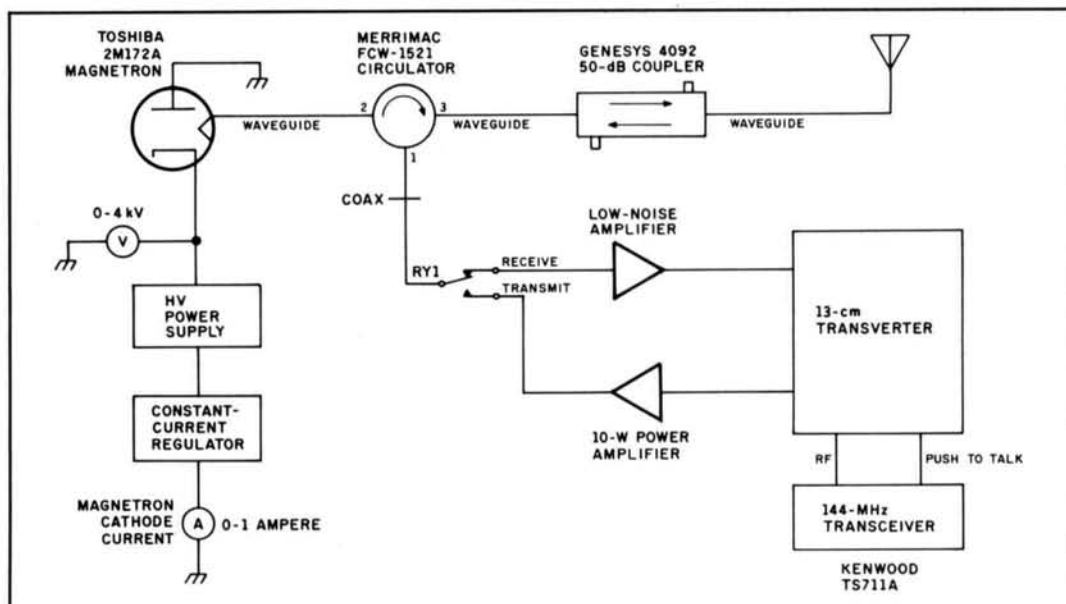

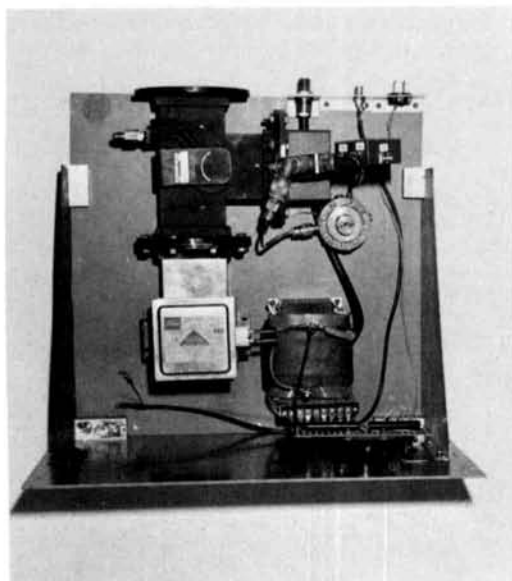Figure 4. 13-cm magnetron transmitter, block diagram.
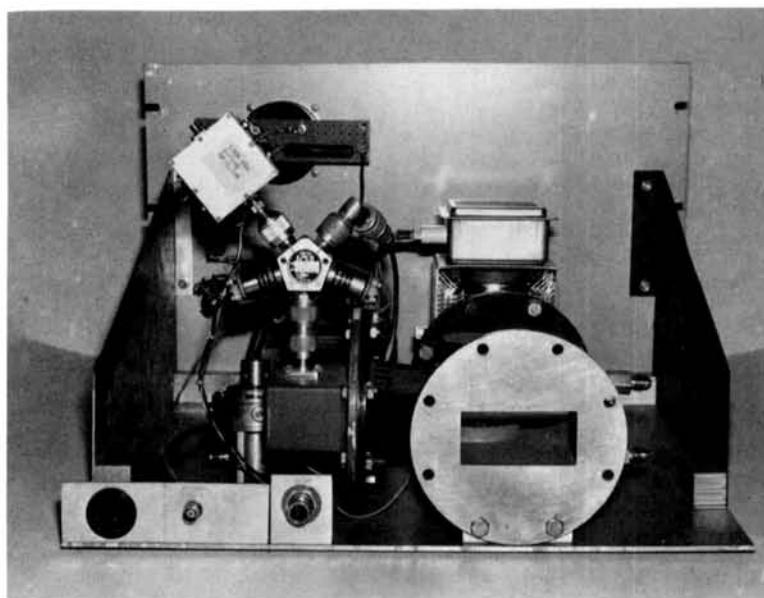
Photo B. RF deck, top view.
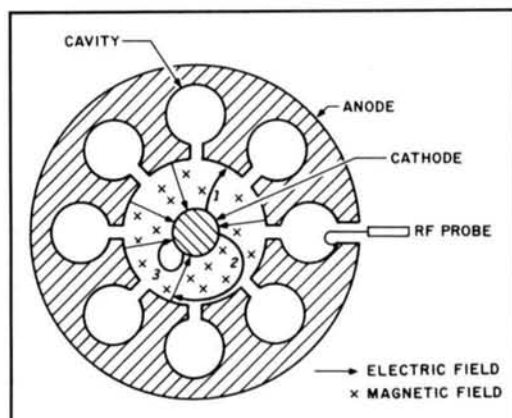

Photo C. RF deck, rear view.

Figure 5. Action of an electron in a non-oscillating magnetron.

port circulator. The circulator load port feeds a dual-directional coupler used for testing, and then the antenna or load. The third port of the circulator, which I call the injection port, is fed from the 10-watt power amplifier through transmit/receive relay RY1, when in the transmit position. Input power for the 10-watt power amplifier comes from the transmit port of the 13-cm transverter, which up-converts the 144-MHz transceiver.

When in receive mode, the signal from the antenna is fed through the dual-directional coupler to the circulator load port. It then goes to the injection port, and through RY1 to the 13-cm transverter receive port, which down-converts the signal to the 144-MHz transceiver.

The DC power for the magnetron is supplied by the magnetron HV power supply. There must be a constant-current regulator in the power-supply circuit to maintain proper magentron operation. This constant-current regulator will allow control of the free-running magnetron power output and frequency. The transmitter has various meters and indicators to aid in system operation and maintenance.

The 13-cm transverter converts the 144-MHz signals from the transceiver up and down. It contains the transmit/receive (T/R) sequencer for proper power control timing.

RF deck

The RF deck, shown in **Photos B** and **C**, contains the major high-power RF components. These are: the oven magnetron, filament transformer, circulator, 10-watt power amplifier, RF transfer relay, and low-noise amplifier (LNA). A dual-directional coupler and high-power load for testing is required, and is included in this section, but it is not a physical part of the RF deck.

Magnetron

The heart of the transmitter is the microwave oven magnetron. The magnetron is basically a diode vacuum tube operating in a magnetic field[3] The magnetron anode consists of a circular group of cavities surrounding the cathode. Each cavity has a narrow slot connecting it to the space around the cathode. The magnetic field is concentrated in the same plane as the cathode.

Magnetic and electric fields

When a weak magnetic field and a strong electric field exists between the cathode and

anode (see **Figure 5**), an electron emitted from the cathode will be attracted almost directly to the anode, and no RF energy will be generated (path 1). As the magnetic field is increased, the direction of the electron traveling toward the anode will be altered into a curve (path 2). If the magnetic field is increased far enough, the electron will fall back to the cathode, never reaching the anode (path 3).

At some critical value of magnetic and electric field, the electron will just graze the gap of the anode cavity and generate an RF field at the cavity's resonant frequency. The interaction of the RF field and the magnetic field at the gaps of the cavities will cause the electrons emitted from the cathode to form bunches that will rotate like the spokes of a wheel past all of the gaps in synchronism with the RF field (**Figure 6**), creating a very large amount of RF energy in each of the cavities.

Mode skipping

A probe inserted into one of the cavities extracts RF energy from the cavity to an external load. If the magnetic field is held constant, and the anode voltage is increased, a point will be reached where electron clouds form another spoke which will not be an even multiple of the number of cavities. When this occurs, there's no longer synchronism with the cavities, and an uneven distribution of energy is supplied to the output cavity. This action is called mode skipping and, if allowed to continue, will damage the magnetron. It is *imperative* that the power supply be designed to prevent mode skipping in the magnetron.

Waveguide choices

RF energy from an oven magnetron is provided by a quarter-wave probe inserted into a length of waveguide. **Photo D** shows a typical oven magnetron and a section of WR-284 waveguide which has been prepared for mounting. **Photo E** shows the magnetron mounted on the waveguide section.

The location of the probe along the waveguide depends on the size of waveguide. The WR-284 or RG-48/U series are the most readily available waveguide components on the surplus market. This waveguide is marginal for the 13-cm band because it's rated for 2.60 to 3.95 GHz. This means that attenuation will start to increase. However, I haven't experienced any difficulty with this size waveguide because I'm not running long sections of it. A better choice of waveguide would be the WR-340
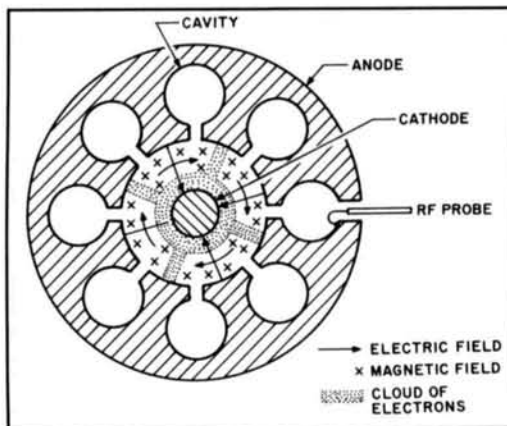

Figure 6. Cloud of electrons rotating in the interaction space of a magnetron oscillator.
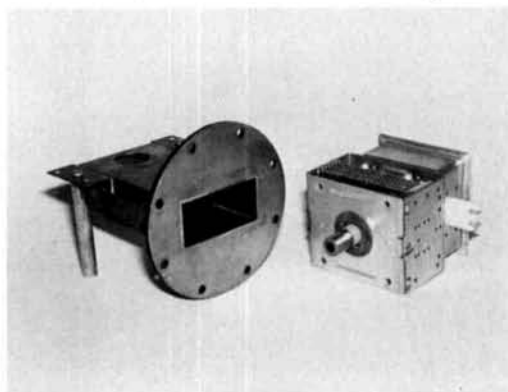

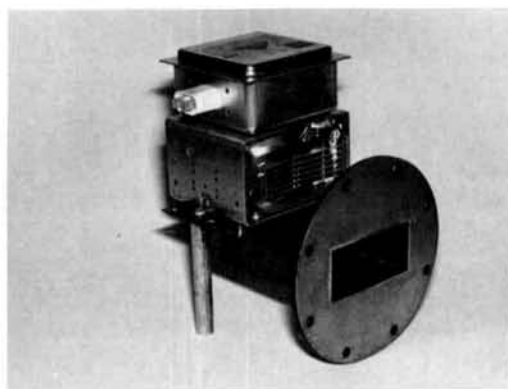Photo D. Typical oven magnetron and waveguide-mounting section.

Photo E. Oven magnetron mounted on waveguide section.

or RG-112/U, which is rated from 2.2 to 3.3 GHz. When the WR-284 waveguide is used, the magnetron RF probe is mounted 1.0 inch from the shorted end. If WR-340 waveguide is used, the magnetron RF probe is mounted 0.8 inch from the shorted end.

Magnetron noise and operating modes

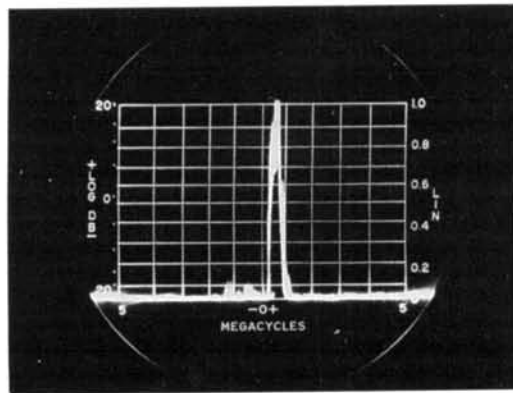When I say that I use a magnetron for a transmitter, I often hear: "The output spec-

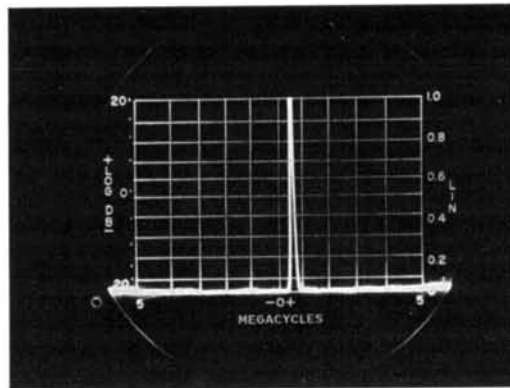Photo F. Oven-magnetron output with filament voltage on.

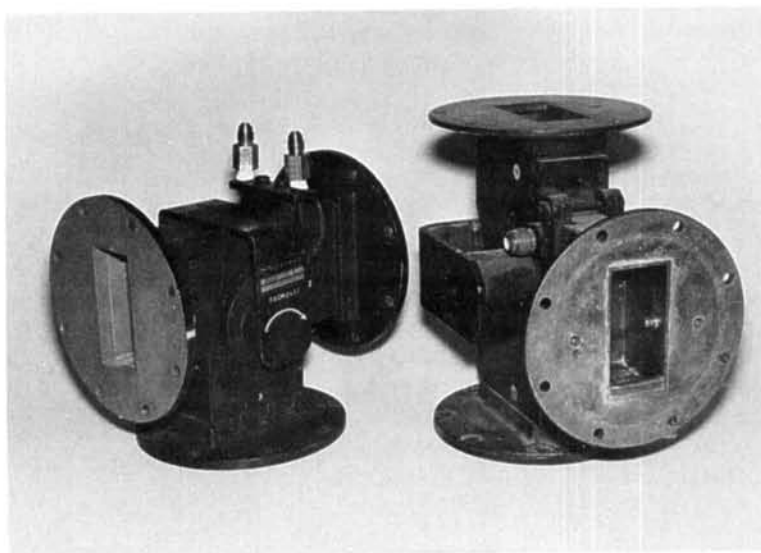Photo G. Oven-magnetron output with filament voltage off.

Photo H. Two typical high-power circulators.

trum of a magnetron is very noisy. How can it be used for communications?" I've found that by turning off the filament voltage after the magnetron reaches the rated power output, the spectrum is very clean. **Photos F** and **G** show the spectrum with the filament voltage on and off, respectively.

As long as the high voltage is applied to the magnetron, the back bombardment of the cathode will continue to keep the cathode hot enough to supply the electrons required to maintain RF power output. Once the high voltage is removed, the magnetron won't oscillate, and the filament voltage must be turned on to restart the magnetron.

Because the magnetron is an oscillator and not an amplifier, it isn't possible to operate the transmitter in SSB, CW, or AM modes. FM and FSK are the only modes available for communication. I've been using the FSK mode to generate a CW-type signal by producing a 10-kHz shift in frequency between key down and key up. As long as I give the other station the correct frequency, we have no trouble working each other.

The frequency allocation for microwave-oven service is from 2440 to 2460 MHz, so it's possible that not all oven magnetrons can be operated within the Amateur 13-cm band. I've only tested two, and in each case I was able to tune them to 2448 MHz at nearly full power output. More testing is required to find out which tubes are best suited for Amateur service.

The tubes I used came from discarded microwave ovens with defective power supplies or timers. I tested several other tubes whose filaments were in good shape, but there was no longer any cathode emission. New tubes can be purchased from service dealers or distributors for less than $100.

Circulator

The circulator is the key to injecting a locking signal into the magnetron at the same time that the magnetron is supplying RF output power to the load or antenna.

A circulator can be constructed as either a three or four-port device. I use a three-port circulator. The adjacent ports of the circulator are effectively connected together in one direction but isolated from each other in the opposite direction. Therefore, the signals can pass easily from the transmit port to the load port, and from the load port to the injection port; but, they will be attenuated in opposite directions.

The waveguide circulator is made by joining three waveguide arms, 120 degrees apart, at a common junction containing a slab of ferromagnetic material. The ferromagnetic material rotates the standing wave pattern so RF coupling can only accomplished in one direction. When circulators are designed to handle high power, they are generally water cooled by wrapping copper tubing

around the central part containing the ferrite material. **Photo H** shows two typical high-power circulators. The one on the left is a model FCW-1521 built by Merrimac Microwave Co.; the one on the right is a model 4095 built by Genesys Systems, Inc.

Because the circulators are built from ferromagnetic material, caution must taken when handling them. They should be mounted away from any magnetic material and protected from jarring due to sharp blows.

Circulators operate efficiently only over a narrow bandwidth, typically less than that of the the waveguide.

Dual-Directional Coupler

The dual-directional coupler measures the forward power of the transmitter and the return loss, or VSWR, of the antenna or load.

The directional coupler is designed to couple power from the transmission line at some designated attenuation level in one direction, and at a much greater attenuation level in the opposite direction. The value of coupling attenuation should be such that the maximum power level at the coupled port is close to the input power rating of the power meter, or other measuring device.

10-watt power amplifier

I found that approximately 10 watts of injection power was sufficient to ensure that the oven magnetron locks on frequency while operating at full power. I built an amplifier using a 7289 tube in a quarter-wave cavity and operate it with 300-volts Eb with 0-volt bias. Some solid-state power amplifiers which operate near this power level are available at flea markets.

Low-noise amplifier

The low-noise amplifier (LNA) is a two-stage, GaAsFET amplifier which uses Dexcel D432 devices that produce about 20 dB of gain with a noise figure of under 2 dB.

Waveguide load

A load for testing transmitters should be designed with low VSWR and the capability to absorb the transmitter's total power without overheating.

A typical waveguide load is made by mounting a large piece of tapered carbon rod at the closed end of the waveguide. The angle and length of the taper determines how well the load is matched. In the case of a high-power load, there must be a good
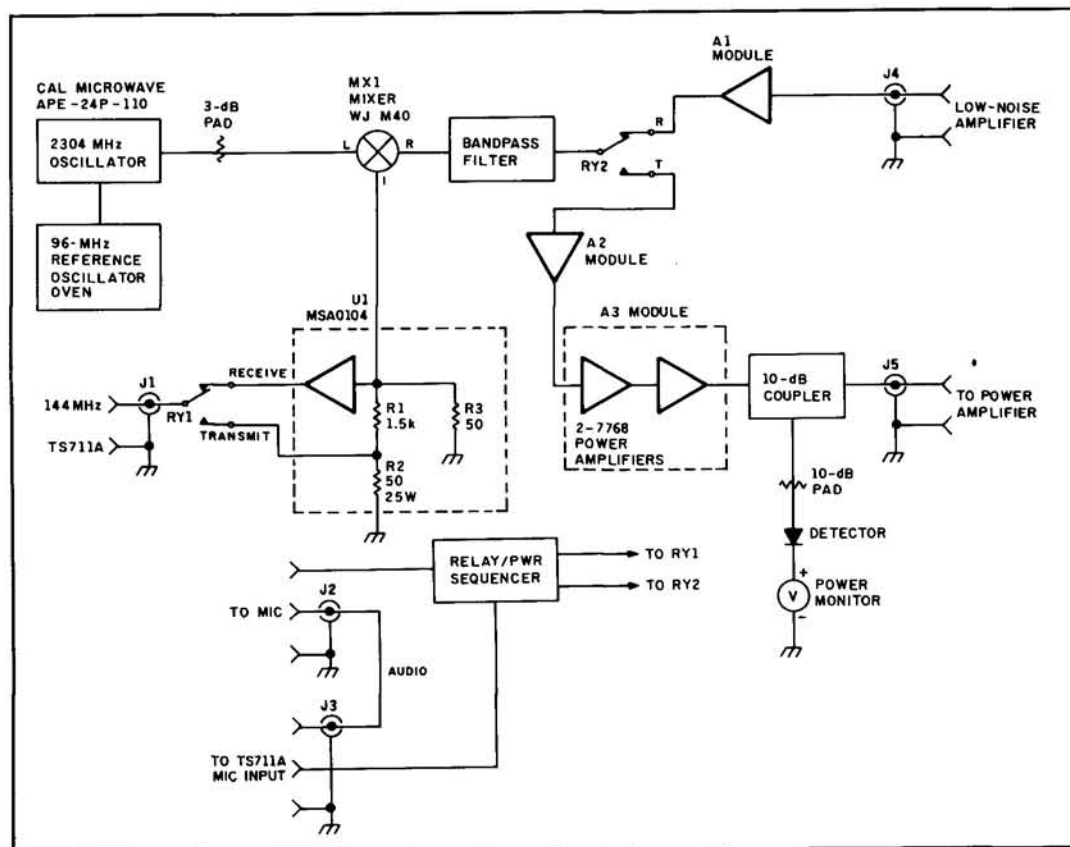

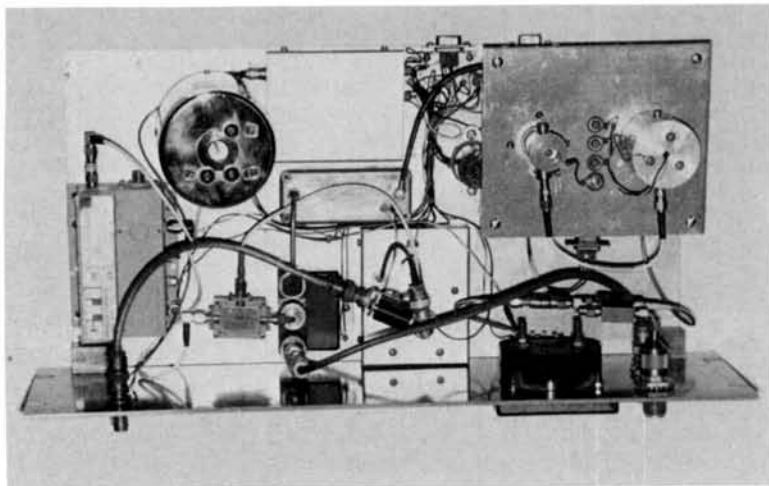Figure 7. 13-cm transverter, block diagram.
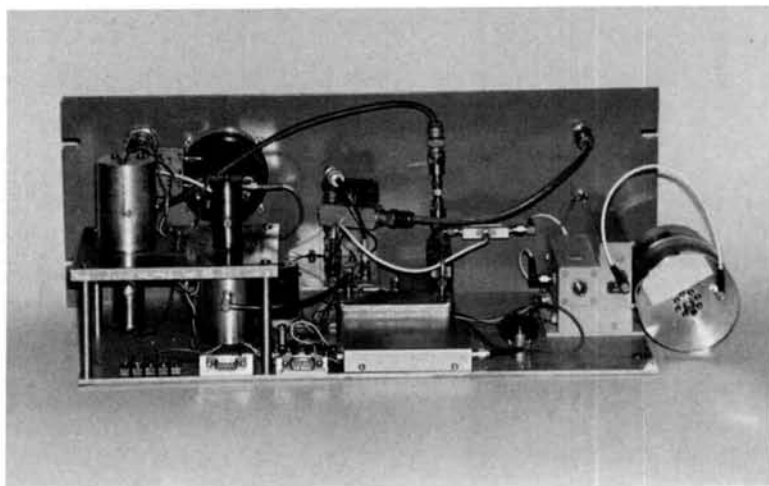
Photo I. 13-cm transverter, top view.

Photo J. 13-cm transverter, rear view.

thermal bond between the carbon absorber and the heat sink.

Water absorbs RF energy well. Many high-power loads are made by creating a section of the waveguide through which water can be pumped in and out. These loads are small and light, but require a great amount of pressurized water to dissipate large amounts of RF power.

13-cm transverter

The 13-cm transverter block diagram, shown in **Figure 7**, will convert RF signals up and down from a 144-MHz transceiver into the 13-cm band. The power output of the 13-cm transverter is about 1 watt on transmit. The noise figure is about 4 dB on receive. **Photos I** and **J** show the top and rear views of the 13-cm transverter, respectively.

Local oscillator

A 2304-MHz local oscillator (LO) in the 13-cm transverter generates a signal at 2448 MHz when using the microwave oven magnetron. If the 13-cm transverter is to be used for Phase III satellite work, or at the bottom of the 13-cm band, the LO to 2256 or 2160 MHz can be changed easily by replacing the oscillator and reference generator. The oscillators I use are from California Microwave Corporation; Communications Technology, Inc.; or Frequency Source West. They are available at flea markets, or through ads in various ham magazines.*

Mixer

The mixer is a surplus Watkins-Johnson M-40 which covers a 1 to 5-GHz frequency range (**Figure 7**). The maximum LO power for the mixer is 23 dBm. The mixer will easily provide 0 dBm output at the RF port when 10 dBm is supplied at the IF port.[1]

A four-pole, interdigital filter is used at the output port of the mixer to suppress image frequencies during transmit and receive. A good match must be provided at the filter input.

Modules A1 and A2 (**Figure 7**) are two-stage, 20-dB gain, transistor amplifiers which use Dexcel D-432 GaAsFET devices. Module A3 is a two-stage, coaxial-type power amplifier, using GE 7768 vacuum tubes in a grounded-grid configuration. Each stage has a power gain of about 12 dB at 1 watt RF output. The input and output cavities are 3/4-wavelength long with tuning slugs that cover the entire 13-cm band.

It has been my experience when trying to operate the Kenwood TS711A or TS811A transceivers at reduced power, that the RF-power output rises to full power (25 watts) for a few microseconds before it settles to lower power. When driving mixer diodes, this short spike of high power can sometimes damage the diodes. I now use a high-power power divider when building transverters, and run the transceiver at full power output. This requires another properly sequenced RF relay, but it's the only way I've found to prevent the loss of valuable mixers.

Push-to-talk line

When going from receive to transmit, or vice versa, it's imperative that the transfer relays be properly sequenced. When going

*One source of local oscillators is: Alan Dickinson, N5BHX, 154 Basswood, San Antonio, Texas 78213.

to transmit, the T/R relays must be in the transmit position before the 144-MHz transceiver goes into the transmit mode. Likewise, when going from transmit to receive, the 144-MHz transceiver power output must drop to zero before the T/R relays return to the receive position. This is accomplished by a delayed push-to-talk line to the 144-MHz transceiver.

Constant-current regulator section

Once the magnetron starts to draw current, it will continue to do so unless some form of limiting is provided. Microwave oven manufacturers use current-limiting power transformers designed to supply the rated voltage and current. Because the current level supplied by these transformers may not be at the value Amateurs need to operate the magnetron, some external means of controlling the current to the magnetron is needed.

There are several ways to build constant-current regulators that will do the job, but most are not easily adjustable under load at the current values required for the oven magnetron. Because high voltages are present, I felt it was necessary to use vacuum tubes.

After considering the many types of tubes that could be used as current regulators for this rig, I selected the 4CX250B power tetrode. It has one of the flattest Eb/Ib curves of any tube available.[5] At a maximum current of 250 mA per tube, I needed four of them operating in parallel to provide the proper constant-current regulator for the oven magnetron.

The schematic diagram of the constant-current regulator is shown in **Figure 8**. The positive terminal of the magnetron HV power supply is tied to the plates of the 4CX250Bs through 18-ohm limiting resistors and a 1-A full-scale meter to measure magnetron cathode current. The screen voltage for the 4CX250Bs is supplied from a 250-volt, 100-mA regulated power supply. The adjustable bias for the tubes is supplied from a negative 68-volt regulated bias-power supply.

To balance the slight tube differences, there are individual bias adjustments for each. The cathode, control grid, and screen grid of each tube is bypassed with 0.01-μF, 500-volt ceramic capacitors. The anodes are bypassed collectively with a 1200-pF, 2500-volt feedthrough capacitor. The current of each regulator tube can be monitored on the multimeter so it can be adjusted for a

balanced condition. The total cathode current of the regulators can also be read from this meter. This provides a means of determining the 4CX250B total screen current. **Photos K** and **L** show the top and rear views, respectively, of the constant-current regulator.

Magnetron HV power supply section

The typical microwave oven magnetron operates at an anode-to-cathode potential of about 3.2 kV with an anode current of 300 to 800 mA — depending on the magnetron power output. Filament requirements
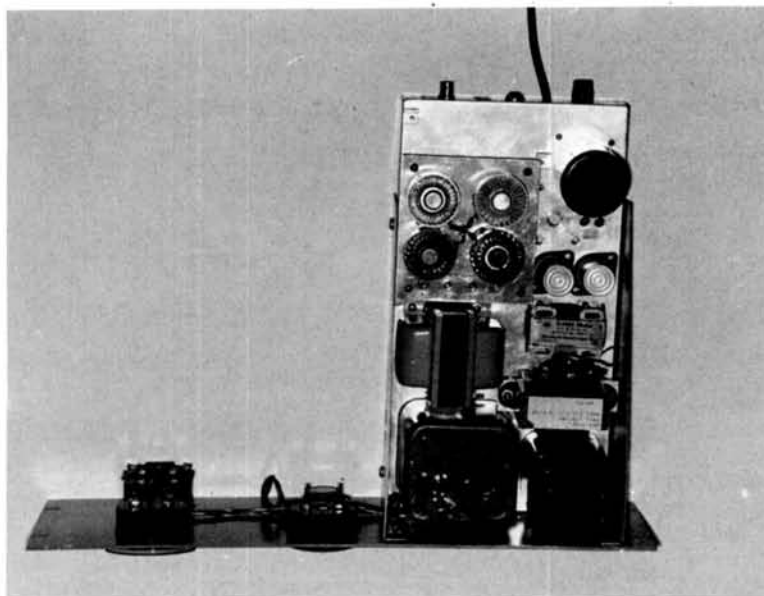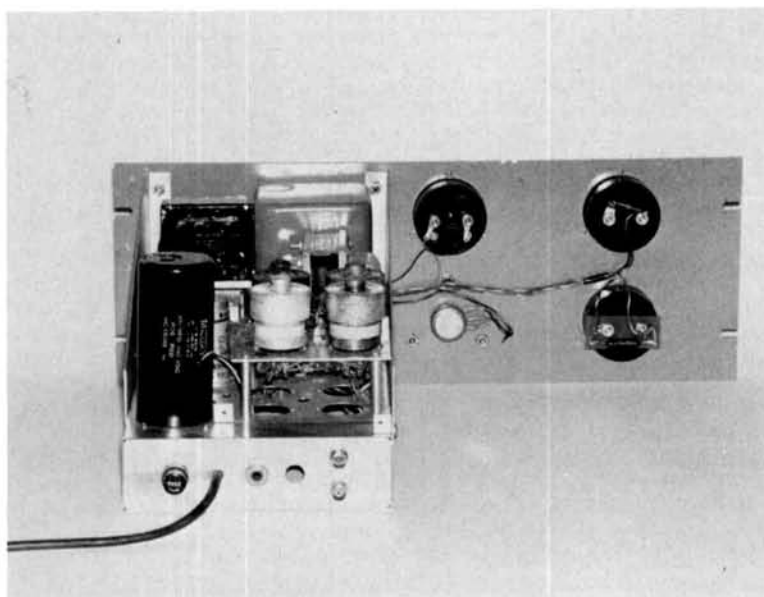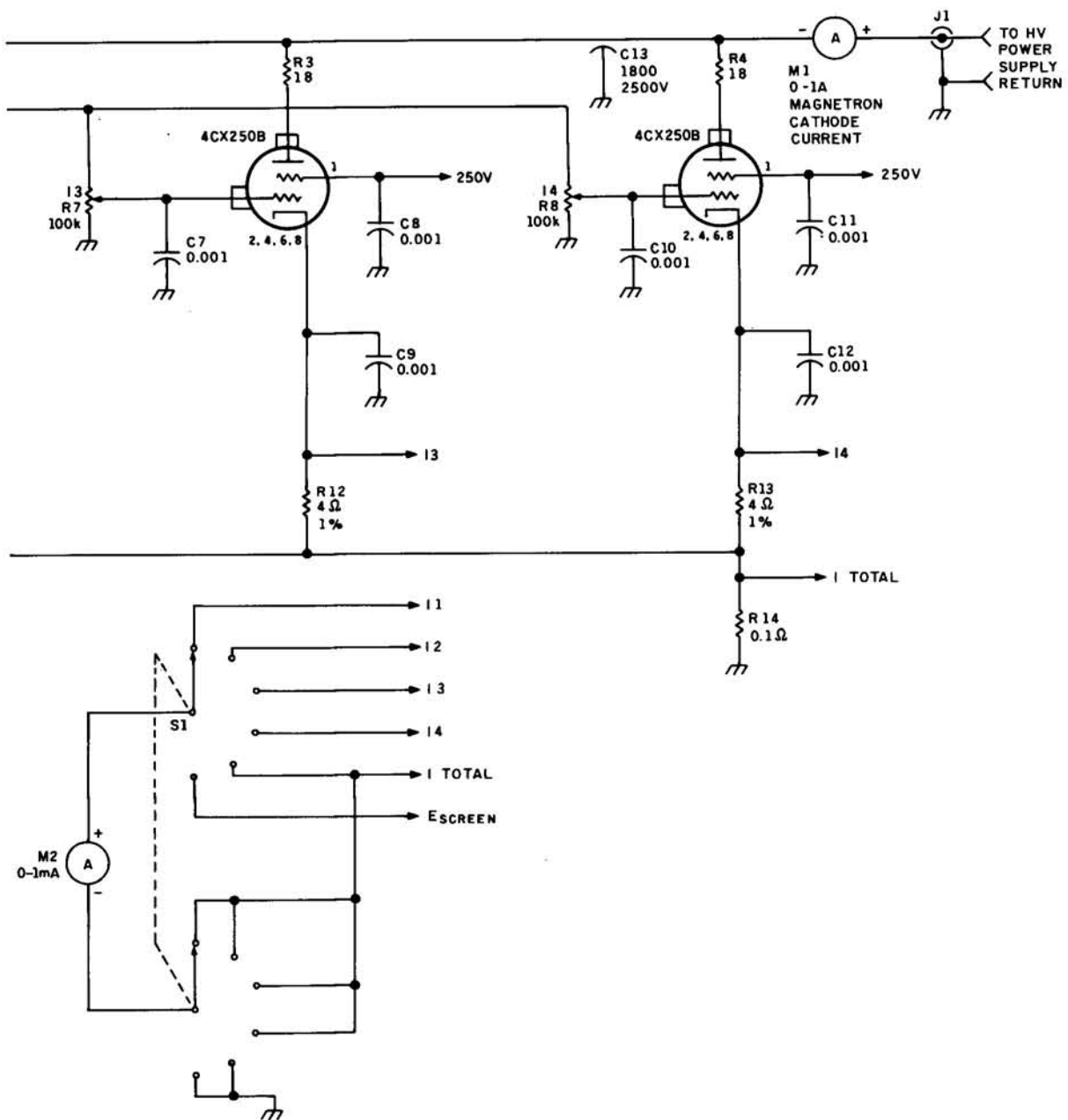

Photo K. Constant-current regulator, top view.

Photo L. Constant-current regulator, rear view.

Figure 8. Constant-current regulator, schematic diagram.

Figure 9. Magnetron HV power supply, schematic diagram.

will be in the 3 to 5-volt range at current ratings of 20 to 40 A. There's a large current in-rush when power is turned on, so some means of current limiting must be provided for both filament and anode supplies. A means of protecting the magnetron from damage due to overheating must also be provided, either by forced air or water cooling.

The magnetron in a typical microwave oven is operated from a power supply that has a current-regulated, high-voltage power transformer and uses full-wave rectifiers with unfiltered output voltage. Consequently, the tube is operated in the pulse mode with a duty cycle of about 50 percent. This is done to prevent mode skipping. In Amateur operation, the tube must operate at 100 percent duty cycle from a well-filtered power supply because the magnetron frequency is sensitive to supply voltage changes. Due to the microwave oven's 50 percent duty cycle, I've found that the power transformer from the the oven isn't "husky" enough to be used in an Amateur transmitter. The magnetron filament is supplied from a winding on the high-voltage transformer. Thus, the transformer can be used for this purpose without surge protection for the filament (required if a separate filament transformer is used). It is necessary to protect oneself, and the circuit, from the transformer's unused high-voltage terminal.

I built the magnetron HV power supply using a 7200-volt center-tapped transformer with full-wave rectifiers into a pi-network filter, as shown in **Figure 9**. The output voltage is controlled by a 30-A Variac®. A time-delay relay in the primary allows the filament to reach temperature before high voltage can be applied. The high-voltage switch is in series with the temperature-sensing thermostats installed on the magnetron and on the water-cooling system, so high voltage can't be applied to the magnetron if the temperature is too high.

To discharge the filter capacitors, a large bleeder resistor is placed across the power-supply output when the high voltage is turned off. The bleeder resistor is removed from the circuit when high voltage is on, because there's no reason to waste power during transmit. A 5-kV voltmeter reads the power supply output voltage. Indicator lights are provided for main power, standby, and high-voltage ON. The power supply weighs over 200 pounds, so it rests in the lowest position of the transmitter rack.

Testing the transmitter

The following pieces of test equipment are required to evaluate the performance of the 13-cm transmitter:
* A frequency meter capable of measuring the transmit frequency to within 1 MHz.
* A power meter and attenuator pads to measure the transmitter power output.
* Directional coupler.
* Spectrum analyzer.

It's also necessary to have some means of observing the spectrum to ensure the magnetron isn't mode skipping. A receiver covering the frequency of interest, with a panadapter that has a minimum of 1-MHz sweep width, can be substituted for a spectrum analyzer. Panoramic Radio, Inc. panadapters with 5-MHz sweep widths, used in the telemetry industry, are available at most flea markets.

Free-running mode

The first tests on the 13-cm transmitter are done in free-run mode; that is, not locked to a stable source. A suitable load is connected to the transmitter output, and the spectrum analyzer is connected to the forward port of the dual-directional coupler (see **Figure 10**). If required, an attenuator pad should be used to prevent damage to the spectrum analyzer. The frequency meter should be connected in a manner appropriate for the type used.

With the power to the transmitter turned on, the magnetron cathode voltage and current is adjusted to the recommended values, and the spectrum is observed. A single line should appear on the screen. If not, the cathode current is readjusted to a value that produces a single line. The line should look similar to that in **Photo F**. Next, the filament voltage to the magnetron is turned off. The line should now look like **Photo G**. The magnetron cathode current is adjusted to lower values and the power output observed. At some lower value of cathode current, the magnetron will fail to operate. These magnetron cathode current and frequency values are recorded for future reference.

Magnetron pushing characteristics

With the filament voltage turned back on, and the magnetron cathode current
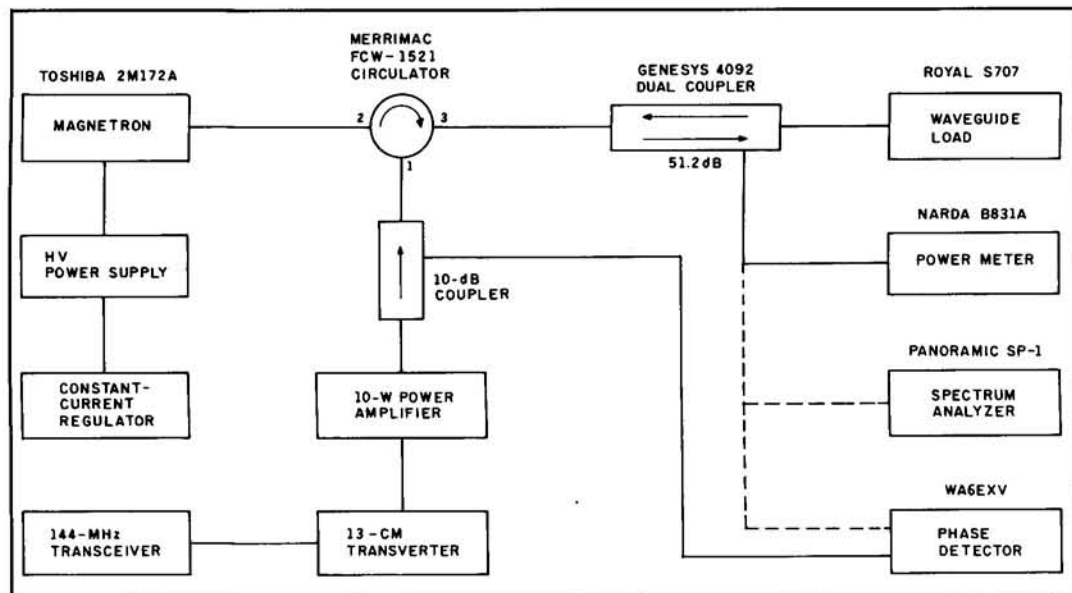
Figure 10. 13-cm transmitter test setup, block diagram.

readjusted for full-power operation, the frequency is measured. This is the magnetron's maximum frequency. As the magnetron cathode current is reduced, frequency and power output decreases. These values are recorded and plotted on a graph of magnetron-cathode current versus frequency similar to the one in **Figure 11**. This curve shows the magnetron pushing characteristics. From this graph, the frequency at which the 13-cm transmitter will be operated is determined and the magnetron cathode current is adjusted to that value.

Magnetron pulling characteristics

The output from the 10-watt power amplifier is connected to the transmit port of the T/R relay on the RF deck. The transmit port of the 13-cm transverter is connected through a suitable variable attenuator to the 10-watt power amplifier input. The attenuator is adjusted for 10-watts output of the amplifier. The 13-cm transmitter is brought up in the transmit mode to the predetermined frequency, and the magnetron-cathode current is adjusted up and down until the magnetron drops out of lock. These two values are recorded.

These steps are repeated with lower and lower power output, and another graph similar to the one in **Figure 12** is generated by plotting magnetron cathode current versus locking power. This curve shows the pulling characteristics of the magnetron. By using the pushing characteristics graph,
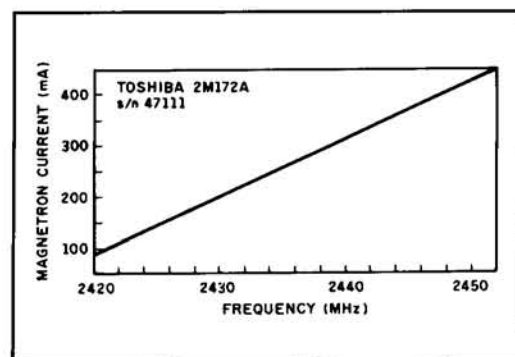
Figure 11. Typical oven magnetron frequency-pushing characteristics.
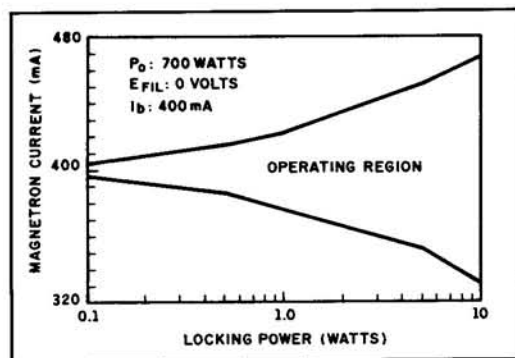
Figure 12. Typical oven magnetron frequency-pulling characteristics.

pulling characteristics graph, and the power levels recorded, it's possible to determine the injection locking power required to operate at a particular output power level and frequency. **Figure 13** is a graph of frequency-locking range versus locking power.
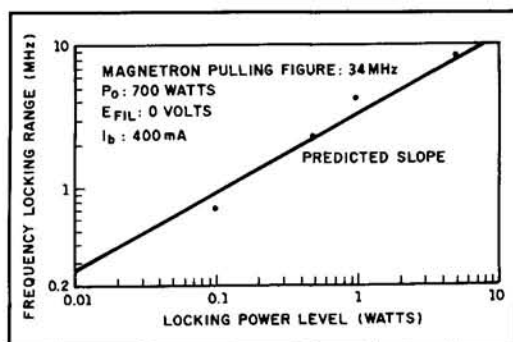
Figure 13. Frequency range for locked operation.

Conclusions

I hope my suggestions for using inexpensive oven magnetrons operating in the injection mode for Amateur transmitters will generate more interest in 13-cm EME.

Although this isn't a construction article, and some of the parts may be difficult to locate, I feel this information will give the serious experimenter some new ideas on how to go about building a high-power 13-cm transmitter.
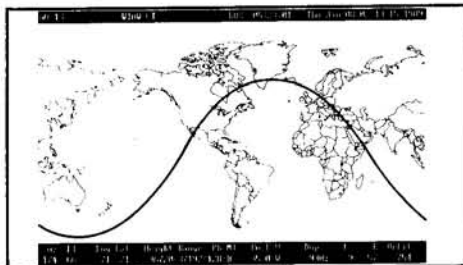
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