The 10-GHz Cookbook

– monster article

Stick to your Gunns.

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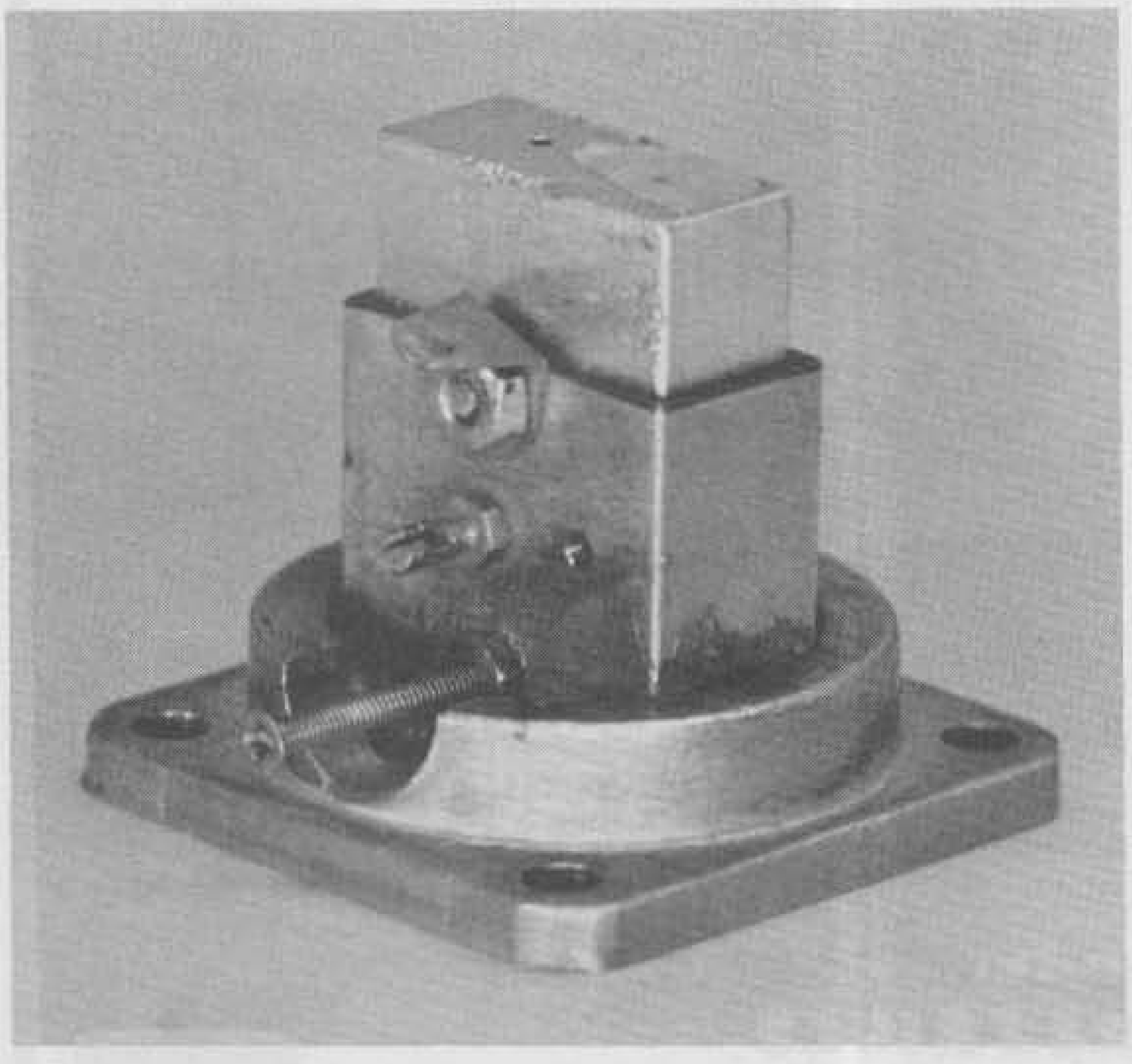


Photo A. The breadboard Gunn-diode oscillator. The waveguide flange is relieved to clear the 2-56 frequency adjustment screw. The positive supply connection is to the turret terminal of the diode mount.

The amateur 10 GHz band offers many fascinating opportunities for both communications and experimentation. Antennas of very high gain are of practical size so that many tens of miles may be spanned with good reliability. The band is a natural for linking of VHF and UHF repeaters, control of repeaters, or control of remote base stations. Activity in the band has been limited by the lack of a good low-cost rf source. A number of transmitters and receivers have been built using surplus klystron tubes, but since surplus items are not generally available to everyone, these designs are difficult to duplicate. In addition, the development of repeater command links or interties requires that the equipment be reliable and compatible with other solid-state gear. Klystron-based designs with the necessary high-voltage dc supplies are certainly not desirable. Gunn-diode oscillators offer an attractive alternative. Properly applied, they will provide up to several hundred milliwatts of stable low-noise rf power.

Gunn-diode technology has been with us for about ten years. In that time, the device has moved from a lab curiosity to a mainstay of microwave engineering. There has always been both commercial and military demand for an inexpensive solid-state microwave rf source. In response to this need, the technology has been pushed rapidly and the price of the diodes has fallen to the point where commercial applications such as radar intrusion alarms, speed meters, and door openers are common. The price of a 10 milliwatt X-band diode is now less than ten dollars. More powerful devices cost more but are still quite reasonable. Actually, some very practical systems may be built with a 10-milliwatt transmitter. Using a 3-foot dish with 36 dB of gain and a 10-milliwatt source, one obtains an effective radiated power of 40 Watts! That is more than ample for most applications.

My objective in writing this article is to create some interest in X-band operation and to show how easy it is to get started. I will describe the operation of Gunn diodes and present a practical oscillator design. The oscillator tunes the entire 10.0-10.5 GHz band with a power capability of more than 20 milliwatts. The oscillator is easily reproduced and is very reliable. One unit has been operating for almost three years and several others have been built. They all have worked perfectly, so I have a lot of confidence in the design.

This is a new area to many amateurs, so I will describe some tests and trade-offs that may be made to optimize a Gunn-diode oscillator for particular applications. The effects of load mismatch upon the power output and frequency of the oscillator were measured and data was taken for two diode types. I will describe both the tests and the results obtained. Afc or phase locking requires electronic tuning of the oscillator. The frequency of Gunn-diode oscillators may be controlled to a limited extent with the dc supply voltage. I made some tests to determine how useful this can be and will discuss the results. Applications for this design are numerous and my objective is to give as much practical data as possible to aid you in putting the circuit to work in your system.

So much for science! Making a Gunn oscillator is fun only if you can do

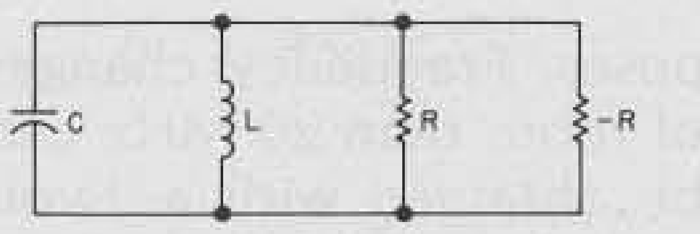


Fig. 1. Negative-resistance oscillator. L and C are the resonant circuit elements. R represents all losses, including output power. The negative resistance of the Gunn diode is represented by −R.

something with it. Part of the article describes a simple transceiver which may be made by adding a mixer to the basic oscillator. This is an ideal device for getting started on the band. It has two immediate uses: as a simple transceiver for communications, and as a Doppler radar. A Doppler-radar processor is included. The processor turns the transceiver into an effective speed meter, door opener, kid watcher, intrusion alarm, or whatever.

The transceiver may be used as a wideband FM link by modulating the dc bias supply and using an FM tuner or receiver as an i-f strip. The basic oscillators are useful as transmitters or as receiver local oscillators in either wideband or narrowband FM systems. Hopefully, someone will use the design as a starting point for an operational repeater command link or other X-band system application.

Gunn Oscillator Operation

Gunn oscillators are negative-resistance oscillators. Fig. 1 is a schematic of a negative-resistance oscillator modeled as a conventional LC oscillator. If the L and C were truly lossless and no power were taken from such a circuit, it would continue to oscillate once started. Real components do have losses and these are lumped into the loss resistance, R, of Fig. 1. Any output power taken from the circuit is also a loss, and that is also

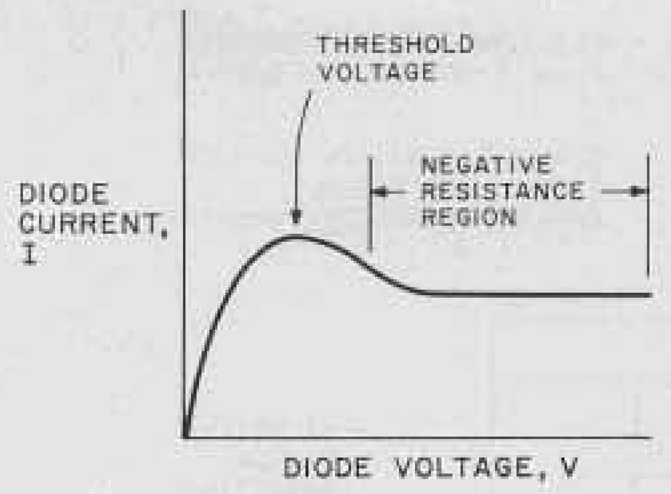


Fig. 2. Gunn-diode voltage-vs.-current plot. Above the threshold voltage, the curve reverses and the current decreases with increasing voltage.

included in R. The effect of a negative resistor is to provide rather than consume power. This is a theoretical concept, but one that can be realized in practice. An LC circuit having more net negative resistance than positive loss resistance will provide sustained oscillations at the resonant frequency of the tank. In practical circuits, the negative R is supplied by tunnel diodes, Gunn diodes, Impatt diodes, and some transistor connections. A Q multiplier is an example of the negative-resistance concept. As the Q is increased, the circuit suddenly breaks into sustained oscillations; more negative R is being introduced into the circuit than there is loss and the circuit takes off.

A Gunn-diode oscillator is simply a microwave cavity resonator to provide the LC circuit and a negative resistance in the form of a Gunn diode.

Gunn diodes are made of gallium arsenide. The GaAs material can have electrons in either of two conduction bands. The electrons in one band happen to have much higher mobility than in the other band. Electron mobility is the measure to the rate of travel of electrons in the material. Greater mobility means higher velocity. In the absence of an applied electric field (voltage across the material), electrons are in the high mobility band. As the voltage across the material is in-

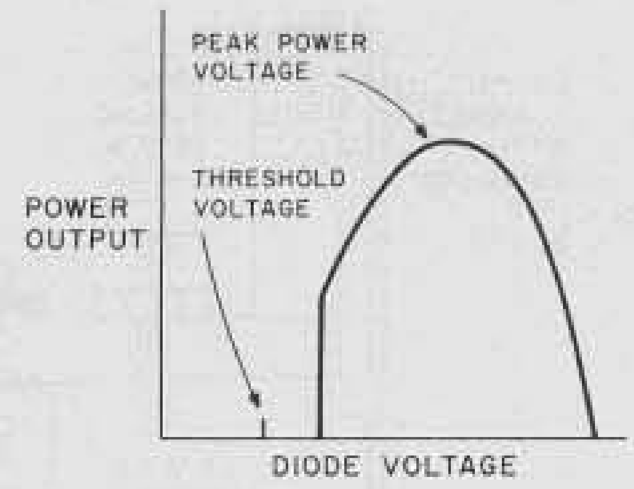


Fig. 3. Gunn-diode oscillator power vs. diode voltage. The peak power voltage will be different at different frequencies.

creased, more move to the low-mobility band. The electron mobility in the material as a whole then becomes the average of the high and low mobilities. This means that the average velocity of an electron drops. Increasing voltage drops the velocity further.

Electric current is the measure of the number of electrons passing a point per second. In positive resistances, the current increases with increasing voltage. In other words, the average electron velocity increases with voltage. In GaAs, the velocity drops with increasing voltage. This means that the current also drops as the voltage is increased and we have a negative resistance.

The electric field intensity where the current begins to decrease is called the threshold field. Fig. 2 shows the current-vs.-voltage curve for a Gunn diode. The current initially rises as the voltage is increased. At the threshold voltage, the curve reverses and the current starts to fall. This occurs at a field intensity of 3200 volts per centimeter in GaAs.

This seems like a lot of voltage, but the active region of the diode is made quite thin and the threshold field occurs at applied voltages of only a few volts in actual diodes. The negative-resistance region occurs just above the threshold voltage, and somewhere above that point oscillations will start.

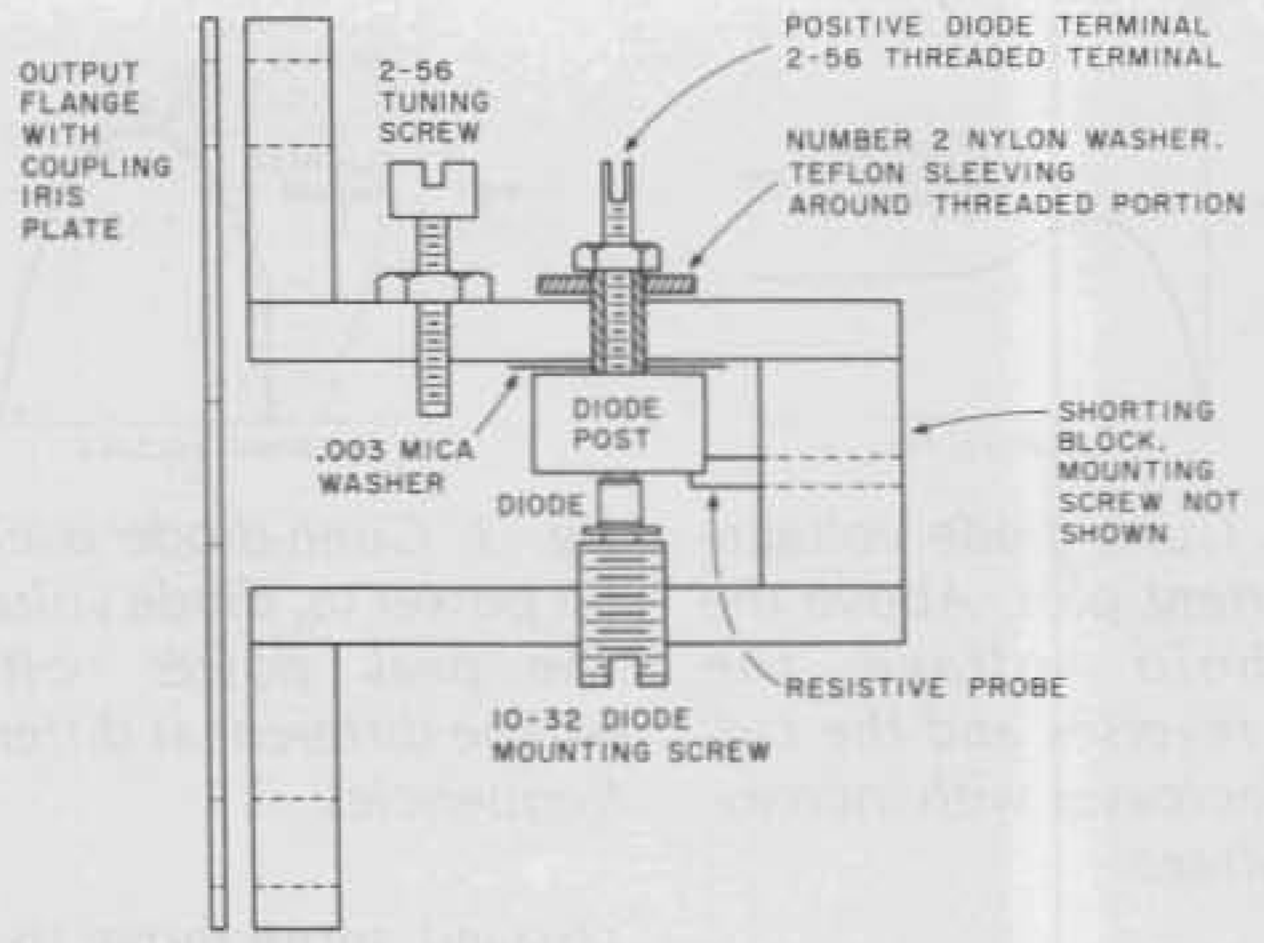


Fig. 4. The Gunn-diode oscillator assembly. Note that the flanged end of the diode (the cathode) is grounded by the diode-mounting screw.

There is one catch. The thickness of the diode must be made to match the travel time of the electrons at the desired frequency of oscillation. This is to ensure that the proper phase relations occur between the electric field and electric current. The diode thickness must be one "transit time length," so that the electron travels the length of the diode in one rf cycle. In other words, the diode thickness must be chosen with the operating frequency in mind, and not any diode will work at any frequency. This is not as bad as it seems. While diodes are characterized at a particular frequency, they will work over ranges of up to two to one.

As explained above, the applied voltage varies the electron velocity. Thus a diode of a given thickness may be voltage-tuned to optimize operation at a particular frequency. In effect, the transit time is changed by adjusting the electron velocity rather than the diode thickness. It is this mechanism which makes the Gunn oscillator tunable with supply voltage.

Fig. 3 shows the effect of supply voltage upon the power output of the oscillator. At some voltage above the threshold, the electron velocity is appropriate to supply negative resistance to the tank circuit. Oscillations start. As the supply is increased, the optimum transit time velocity is obtained and a point of maximum power output occurs for that frequency. If the tank is tuned to another frequency, a slightly different supply voltage will yield maximum power output. Above the maximum power voltage, the power drops off and oscillations finally cease. A typical low-power X-band diode will have a threshold voltage of 3 or 4 volts and will operate from 6 to 10 volts.

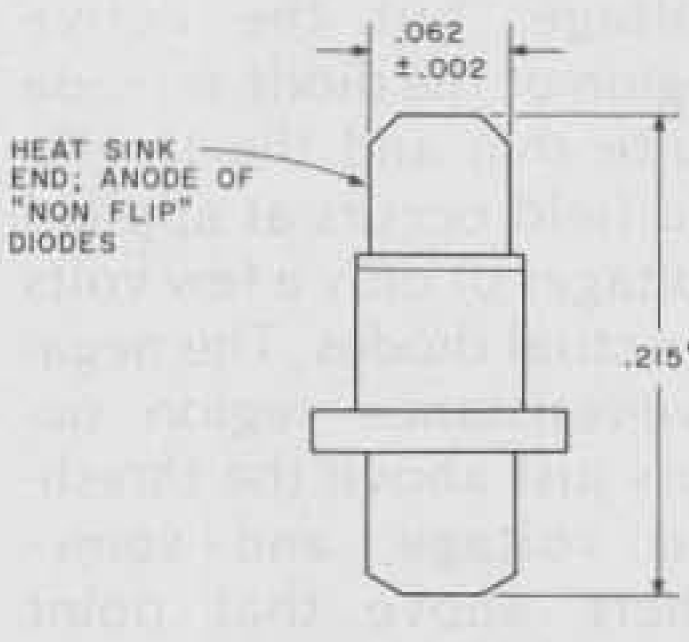


Fig. 5. Gunn-diode package.

Changing the transit time by adjusting the supply in effect "pushes" the resonant frequency of the tank circuit. The diode wants to make negative R at a different frequency than the tank, but the high Q cavity resonator dominates and only a slight frequency shift is obtained. This is enough to be practical for some afc purposes. Frequency changes of more than 20 MHz can be obtained with a 2-volt supply change. Some amplitude change also occurs, but most FM communications systems or mixer LOs can handle amplitude variations of up to 3 dB with no problem.

Gunn diodes have a problem with low-temperature starting. Both the power peak voltage and starting voltage increase as the diode temperature is lowered. Be sure to operate an oscillator well above the room-temperature starting voltage if low-temperature operation is intended.

Building a successful Gunn oscillator reduces to the essential problems of selection of an appropriate diode and installing it in a suitable resonator. Either coaxial- or waveguide-cavity resonators may be used. Low-stability designs having several GHz of tuning range are generally done in coax cavities. High-stability designs tend to use waveguide because of the higher cavity Q which may be obtained. One major factor in getting an oscillator to work is the suppression of spurious resonances in the cavity. The Gunn device has negative resistance over a wide bandwidth and will oscillate easily at resonances other than the desired one if care if not taken. Resonances in the bias chokes or feedthrough capacitor, higher-order waveguide modes, and coaxial modes involving the diode mount are all possible culprits. An effective cure for some of these problems is the inclusion of a lossy material in the cavity at a point where energy is dissipated only by the undesired resonance. This solution was applied to my oscillator in the form of a piece of pencil lead positioned to absorb energy from a coaxial resonance in the diode mount at 13 GHz. Without the loss material, the oscillator went weakly at 13 GHz and no output was obtained in the amateur band. With the parasitic suppressor present, it always works at the correct frequency and starts easily.

Oscillator Construction

The Gunn oscillator is constructed from standard 1.0" by 0.5" X-band waveguide. The EIA and JAN designations for this guide are WR-90 and RG-52/U respectively. The oscillator cavity is a one-half-wavelength resonator with a circular output-coupling iris. Fig. 4 is a side view of the internal oscillator assembly. The diode is mounted across the narrow dimension of the guide and is parallel with the electric field in the cavity. The diode and its mount effectively short the guide in the plane of the diode-mount centerline. Thus the resonant length of the cavity extends from the center of the diode mount to the plane of the coupling iris. The presence of the iris lowers the resonant frequency of the cavity slightly. To ensure that the band may be tuned, the cavity is made about 10 percent short. The cavity is then tuned to the desired frequency with the 2-56 tuning screw. This is located at a point one-quarter wave from the iris. The electric field intensity is greatest at that point and the screw has the most effect. The cavity tunes the 10.0- to 10.5-GHz band and several hundred MHz above and below with the dimensions given.

Gunn diodes come in a variety of package styles. Most use an internal "flip-chip" construction to make the heat sink the cathode. This permits use of positive-bias supplies with respect to the heat sink. This does, however, increase the package cost.

Low-power diodes can be made in "non-flip" packages provided a means is provided to remove heat from the anode. To do this, an effective but dc-isolated heat sink is required. This oscillator is designed to use "non-flip" diodes while having the desirable feature of a positive power-supply input with respect to waveguide ground. For "non-flip" diodes such as the Alpha type DGB-6844C or Microwave Associates type 49508 used in this oscillator, the anode is the heat-sink end of the package as indicated in Fig. 5. The cathode is the end with the sealing flange. Fig. 4 shows the cathode (flanged) end of the package inserted in the grounded diode-mounting screw. If other diodes are tried in the oscillator, be sure to determine which end of the package is the anode. Remember that unless a diode is designated a "non-flip" type, the cathode will most likely be the heat-sink end of the package.

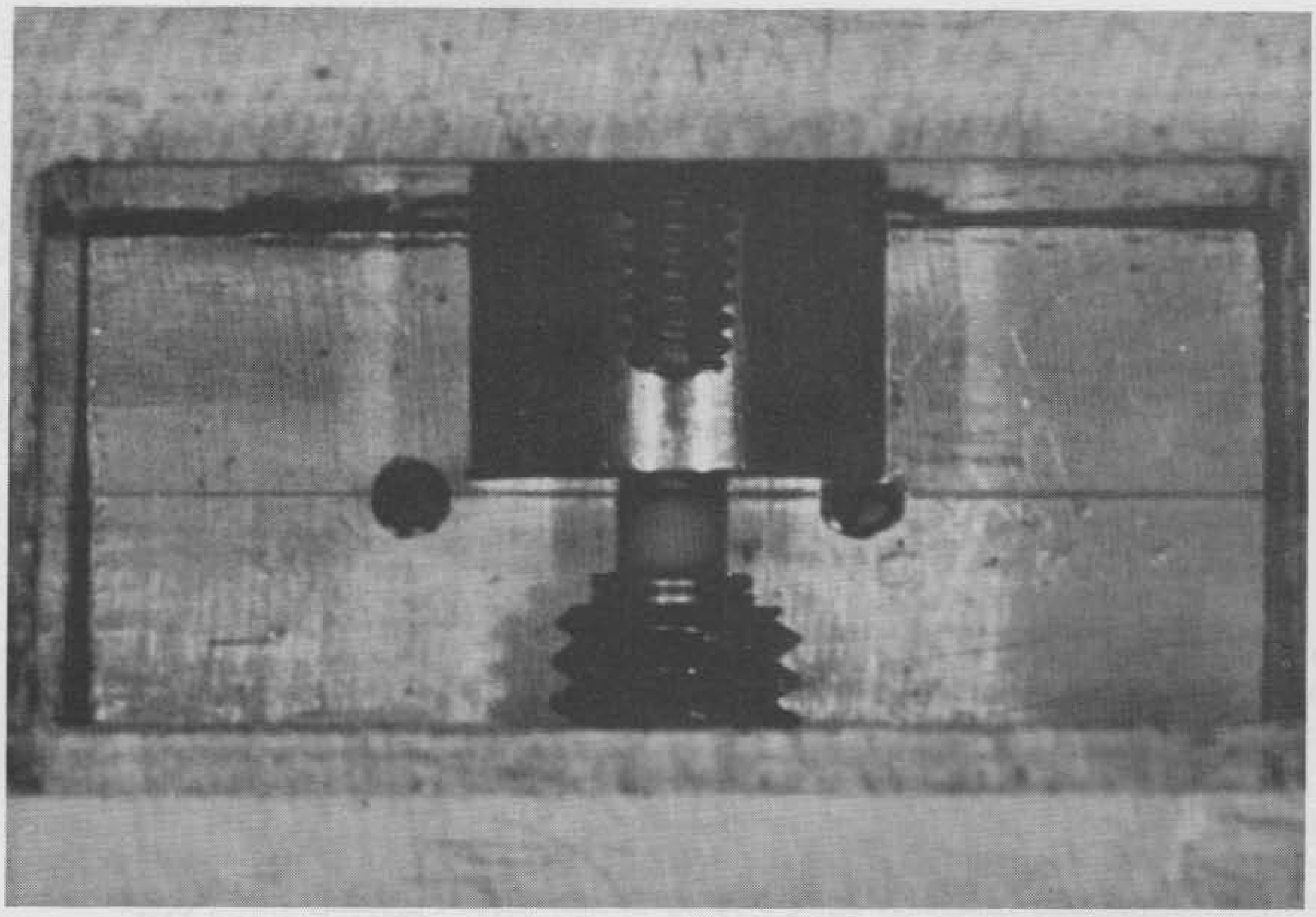


Photo B. Interior view of the oscillator cavity. The Gunn diode is mounted between the heat-sink post and the 10-32 diode-mounting screw. The end of the resistive probe is to the right of the mounting post. The 2-56 frequency adjustment screw protrudes into the cavity from above and in front of the diode-mounting post. The hole in the shorting block to the left of the diode mount is for a trial loss probe location.

Fig. 6(a) is a detailed drawing of the waveguide cavity. The diode mount is installed in holes B and C. Be sure to hold the dimension from these holes to the face of the flange to ensure that the cavity will resonate in the band. There are several varieties of waveguide flange. The intent of the cavity drawing is to use a flange such as a UG-39/U. The waveguide will pass through the flange and should be flush with the face. This will maintain the proper dimension from diode mount to the output iris.

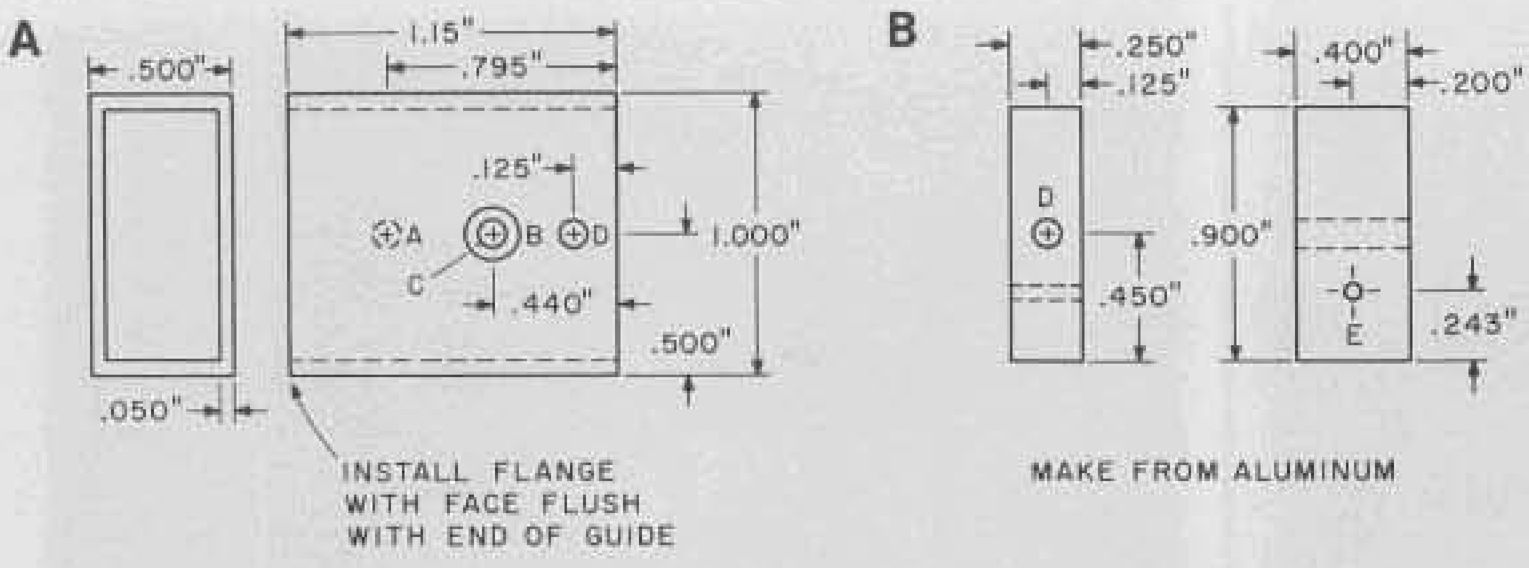
The shorting block, Fig. 6(b), is made from a piece of aluminum. The photo of the breadboard version of the oscillator shows a slightly longer shorting plug. This was to provide a handle for ease of adjustment during the initial design. Make your short as indicated in Fig. 6(b), as it is correct. Hole "E" in the shorting block is for insertion of a resistive probe of common mechanical-pencil lead, as shown in Fig. 4. This is the lossy material which suppresses the undesired spurious oscillation at 13 GHz. An alternative approach to the shorting block is to use a simple plate soldered in the plane of the inner surface of the block. This may be somewhat easier to build, but the probe installation is more difficult. This option applies to the oscillator only. The transceiver version described below requires that the short be removable and the block shown should be used.

The diode mount is shown assembled in Fig. 4 and the detail parts are sketched in Fig. 7. The mount has to do several things at once—match the low diode impedance to the cavity, dissipate heat from the diode, and apply dc bias to the diode while keeping the rf inside the cavity. The heat-sink post, Fig. 7(b), is made from 0.312-inch aluminum rod. It is first drilled through with a number 52 drill to clear the anode end of the diode. This gives a minimum clearance hole diameter for improved heat sinking. It is then drilled at one end only to a depth of 0.100 inch and tapped for a 2-56 thread.

The diode heat-sink post is mounted in the cavity with a 2-56 threaded turret terminal which will be the positive supply connection. Insulation is by means of a nylon washer on the exterior of the guide, Teflon™ sleeving on the threaded portion of the terminal, and a mica sheet insulator between the diode post and the interior wall of the waveguide. The mica forms the insulator of a parallel plate capacitor consisting of the diode post and the interior wall of the waveguide. I used .003-inch mica cut from a TO-3 transistor insulator. The capacitance is more than 20 pF and it is essentially a short circuit at 10 GHz. No rf leakage occurs. A small amount of heat-sink compound should be applied to each surface of the mica insulator. Clean off the excess after assembly as it could cause power loss or frequency drift if left in the cavity.

The 10-32 diode-mounting screw is made from either brass or aluminum. Brass is permissible from a thermal standpoint because most of the heat flow is from the anode end of the diode.

The waveguide output flange is soldered to the output end of the cavity waveguide. Take care that the surface of the flange is flush with the end of the waveguide. Spacing it back will increase the length of the cavity. One caution: Choke-style flanges should not be used on the oscillator. They will not properly clamp the output iris plate and this may change the effective cavity size. Flat



Hole Data

Hole	Data	Function
A	Tap 2-56 far side	Cavity tuning screen
B	Tap 10-23 near side	Diode-mount ground screw
C	Drill #35	Diode-mount dc input terminal
D	Drill #32	4-40 short mounting screw
E	Drill #60	Resistive probe

Fig. 6. Oscillator cavity details. (a) Waveguide cavity. Make from standard .500 x 1.00 X-band guide, EIA WR-90 or JAN RG-52/U. (b) Shorting block.

flanges should be used.

The intent of the removable output-coupling iris plate is to permit easy adjustment of the output coupling. Some applications, such as receiver local oscillators, require only a few milliwatts of power. The power may be reduced and stability greatly increased by using a smaller iris.

The iris plates may be made from ten- to forty-thousandths copper or brass sheet. I used 10-thousandths copper sheet. The iris hole is the waveguide centerline. The output hole diameter may be either .290 or .320 inches as discussed in the section on testing. Smaller diameters can be used to reduce power output. If the iris is much larger than .320, the cavity Q becomes very low and the oscillator does not work below 10.5 GHz.

Assembly of the oscillator should be done in the following order. First, solder the output flange to the cavity and remove all flux. Next, install the diode-mounting post as described above. Do not install the diode itself. Install a resistive probe of .040-inch soft pencil lead in the hole in the shorting block. It should extend into the cavity 0.150 inches. It may be held in place by means of tape on the outside surface of the block until the oscillator is tested. After testing, secure the probe with a drop of glue. The shorting block is next inserted into the cavity and fastened with 4-40 hardware. This hardware should be tightened to the final torque prior to installing the diode. If it is tightened after the diode is installed, the resulting deformation of the cavity may break the diode. Now install the diode. Put a tiny amount of heat-sink goo on the diode anode and cathode pins. Remember the heat-sink end goes to the capacitive mounting post. The flanged end is the cathode and goes to ground. Tighten the 10-32 screw so it is just snug. If a lock nut is used, hold the 10-32 screw from rotating while the lock nut is torqued. This will prevent crushing the diode package. The final steps are to install the tuning screw and the output iris. The iris is clamped between the output flange and the flange on the mating waveguide. Start out with the .290-inch-diameter iris. The oscillator is now ready for test.

Operation and Test

Upon completion of the oscillator, it may be put to use in your particular application. My objective in writing this article was to give an easily-reproduced design which could be used for a variety of applications from receiver LOs to simple transmitters. The test equipment to completely characterize a microwave oscillator is not all that complex, but it certainly isn't found at your corner electronics outlet. Some amateurs have access to commercial or surplus test gear which is of great aid in getting started on X-band. Others have only a scope and VOM and will build this oscillator or the transceiver version described later on as a first project in X-band.

In order to ensure that the design was sound and to obtain enough information to help others apply the circuit to their projects, I took a lot of data to characterize the circuit. With this information, the oscillator may be used with some advance knowledge of how it will behave. The description of the tests performed is provided in case others who can get ahold of the gear wish to repeat the tests or test their own oscillator designs, and to indicate to those who will just build the circuit how the data is obtained. Before getting into the rf testing, here are a few cautions with regard to dc power supplies for Gunn oscillators.

Dc power must be applied to Gunn diodes with some care. The negative-resistance effect extends down to dc, as illustrated in Fig. 2. This can cause dc supply regulators to misbehave. Generally, a series-pass regulator gets very confused when decreasing the voltage increases the current being drawn. The regulator may oscillate and overshoot. The Gunn device may well disappear in the ensuing excitement. Fig. 8 shows a safe method of powering the oscillator. A current-limited supply is used. In shunt with the supply is a husky zener diode which limits the maximum voltage which can be applied to the oscillator to a value of a volt or so above the operating voltage. This will prevent burnout on turn-on transients or if the

Minimum and Maximum Power into 2 to 1 vswr vs. frequency

Diode #	Current mA	10.0 GHz	10.1 GHz	10.2 GHz	10.3 GHz	10.4 GHz	10.5 GHz
1	140	15-29 mW	17-28 mW	18-32 mW	15-35 mW	20-34 mW	22-34 mW
2	150	18-34 mW	20-34 mW	20-34 mW	19-30 mW	18-34 mW	18-48 mW
3	150	17-25 mW	17-28 mW	20-35 mW	18-38 mW	21-37 mW	20-35 mW
4	100	9-22 mW	9-19 mW	10-25 mW	10-22 mW	10-22 mW	10-22 mW
5	125	9-20 mW	7-21 mW	9-18 mW	12-24 mW	14-25 mW	25-12 mW

Table 1. Oscillator performance vs. load vswr and frequency. This table indicates the oscillator power output for five different diodes at frequencies from 10.0 to 10.5 GHz. The load vswr was varied through all phases of a 2 to 1 mismatch. Diodes 1 through 3 are Alpha type DGB 6844C operated at 8 volts. Diodes 4 and 5 are Microwave Associates type MA 49508 operated at 7 volts.

supply oscillates. A series RC circuit consisting of a .1 µF capacitor in series with a 33-Ohm resistor keeps the supply impedance down in the low megacycle region and prevents low-frequency breakup of the oscillator output. With the diodes specified, the heat-sink end of the package is the anode and the diode is installed with this end inserted in the capacitive mounting post. The flanged end of the diode is the cathode and is grounded to the waveguide with the 10-32 mounting screw.

A word about current limiters. The threshold current of the Gunn device is much higher than the operating current. The current limiter on the supply should be set well above the threshold current. For the diodes used here, 500 mA is a good setting.

If the current limiter is set at the operating current, the supply will limit on the low-voltage side of the threshold voltage and the operating voltage will not be achieved. From Fig. 2 it may be seen that there are two points at which the diode will draw the same current, one above and one below the threshold voltage. Don't worry about protecting the diode from excessive current. In this case, lowering the voltage *increases* current, so a normal current limiter does not help. Just set up the supply for the proper voltage and make sure the current limit is set to 500 mA. Then connect the Gunn-diode circuit. If the current limiter is set as above, it is okay to just switch the supply off and on with the power switch. Do not turn up the voltage slowly because the diode will be subjected to more current than if power is suddenly applied. Using these methods, I have yet to lose a Gunn device. Supply oscillations may be checked by connecting a scope across the supply. If the dc line has only dc on it, you can assume that all is well. If oscillations are present, they are generally of high amplitude (several volts) and are easily detected. If this does occur, one fix is to adjust the R and C of Fig. 8. Reduction of the hole in the coupling iris plate may also help. No difficulty was encountered with supply oscillations for a variety of Gunn diodes tried in the cavity provided the circuit of Fig. 8 was used. Dc supplies included commercial and home-built bench supplies and the three-terminal regulators used in the Doppler processor described below.

To set up the oscillator for test, there are only three adjustments: the tuning screw to set the frequency, the output iris diameter which determines load stability and power output, and the depth of the parasitic suppression probe. The tuning screw should be set at minimum penetration of the cavity. The resistive probe should penetrate about .150 inches into the cavity. With the .290-inch iris installed, the oscillator should make at least 10 milliwatts of output. If it does not appear to be oscillating or if it is oscillating weakly (a −20 dBm output), insertion of the resistive probe to a greater depth is indicated because the diode-mount resonance at 13 GHz may be in the act. The three models of the oscillator worked fine with the probe at .150-inch penetration, so you should not have to adjust it. It is not very critical. Once oscillations are obtained, the tuning screw is used to set the operating frequency. The unit will easily tune the 10.0- to 10.5-GHz band with either diode installed.

The selection of output iris diameter depends upon application. To determine which diameter is best for

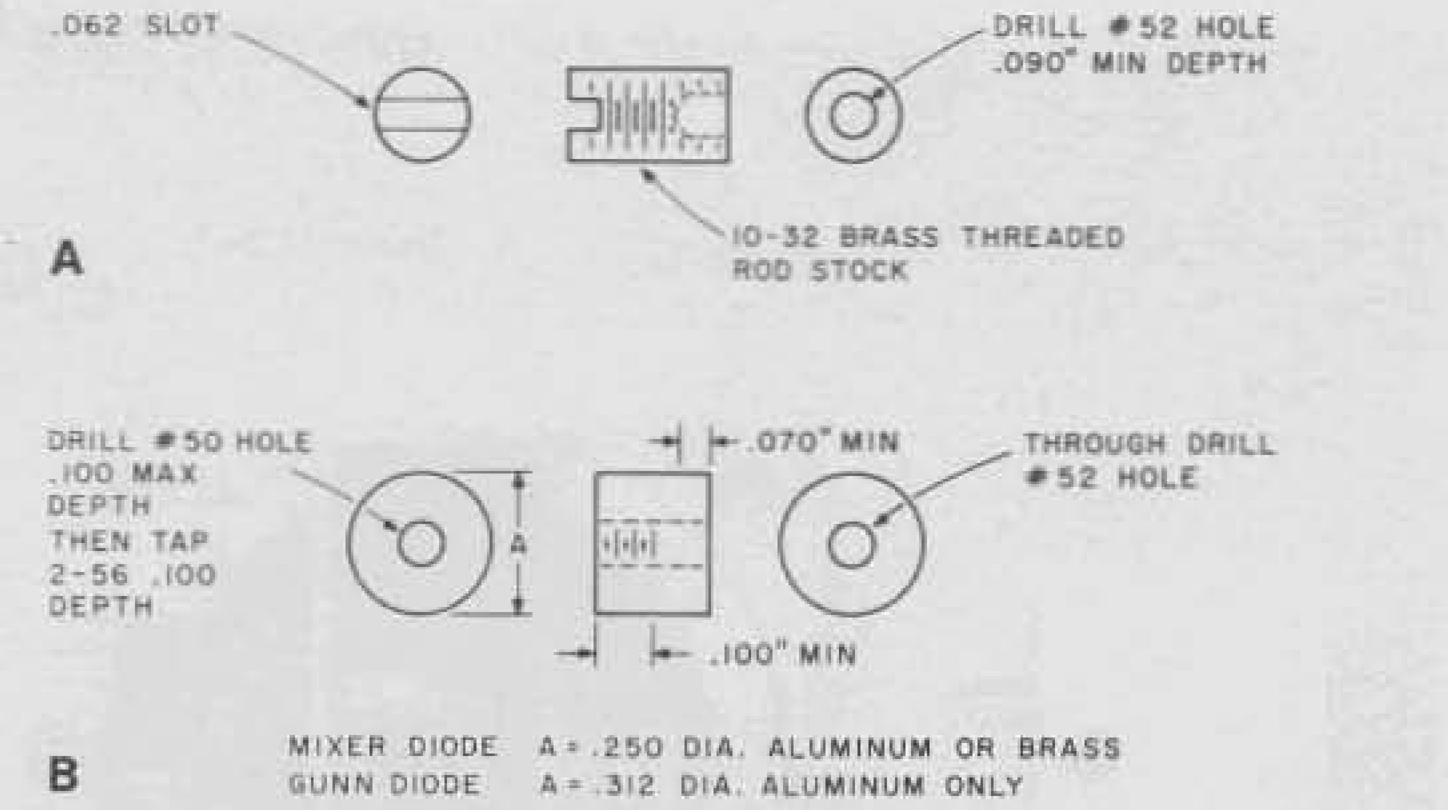


Fig. 7. Diode-mount details. (a) Diode-mounting screw. (b) Diode heat-sink post. The diode heat-sink post is first drilled through with a number 52 drill. The hole is then enlarged to a number 50 size and tapped for the 2-56 turret terminal. The number 52 diameter must be maintained for a depth of at least 0.070 inches to assure proper heat transfer from the diode.

your use, review the tests and test data I obtained.

A shift in load impedance will change both the frequency and power output of any oscillator, crystal, LC, or a microwave type. I made several tests to evaluate the effect of load shifts on this circuit. In addition, the ability to tune the frequency of the circuit with the supply was tested. I found that if the load vswr is less than 2 to 1 and its phase is stable, the frequency will pretty well stay put. If the vswr is controlled and it is less than 2 to 1, the supply may be used to make corrections in the oscillator frequency of up to 20 MHz.

Fig. 9 is a sort of schematic of the waveguide setup I used to test the oscillator. The setup allows the power output and frequency to be measured and a vswr of any desired magnitude and phase to load the oscillator. The oscillator is connected to the main line of a cascade of three directional couplers. The first coupler samples the output power and frequency. The power is detected and displayed on meter M3. A cavity wavemeter in the line absorbs power at its resonance and causes a "suck-out" or dip on M3 when tuned to the oscillator frequency. The next two couplers form a reflectometer which reads the forward and reflected power from the load as seen by the oscillator. M1 reads forward power and M2 reads reverse power.

At the output of the last coupler, a device called a slide-screw tuner is connected. This is followed by a matched waveguide load.

The slide-screw tuner is a simple way to get an adjustable vswr of any phase. It is useful in load tests such as this or as an impedance-matching device. The VHF equivalent is a single-stub tuner which may be moved along the line. Mechanically, the slide-screw tuner consists of a probe through the broad wall of the waveguide (often a screw) which travels in a slot in the waveguide wall. The probe is supported by a slide plate on the outside of the guide. The probe when inserted into the guide is equivalent to a capacitor, the value of which is proportional to the depth of penetration. The depth of penetration controls the magnitude of the imaginary part of the vswr thus created. The position of the probe along the guide controls the phase. The real part of the load is sup-

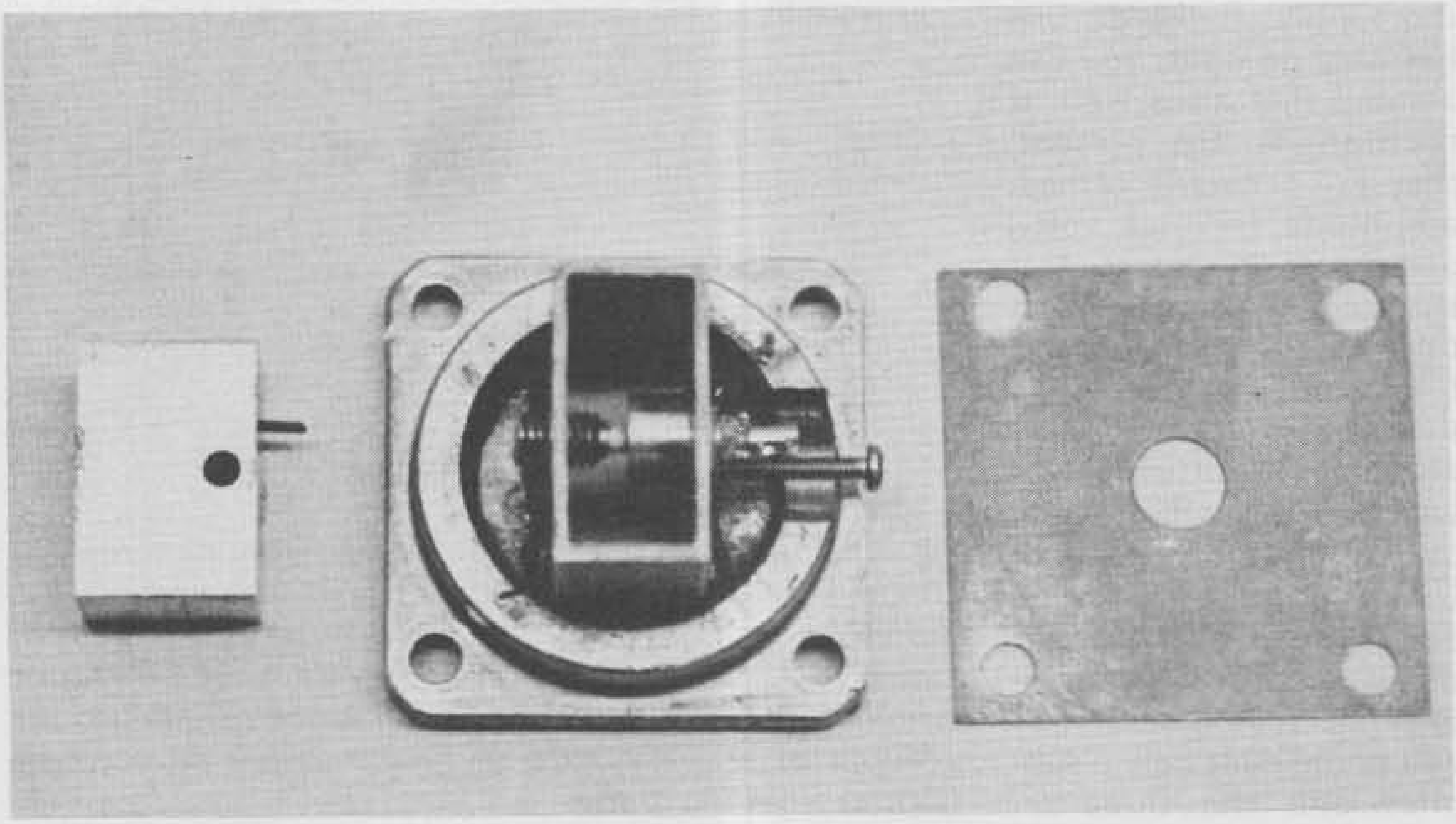


Photo C. The partially-assembled oscillator. The breadboard version of the oscillator is shown with the shorting block and iris removed. The lossy resistive probe extends from the shorting block into the cavity. The removable iris plate permits the output coupling to be easily adjusted.

plied by the waveguide load beyond the tuner. By moving the probe along the guide, a fixed vswr load is effectively rotated through all phases.

I tested my oscillator with load vswrs of 2 to 1. Most waveguide circuits into which such an oscillator will operate may be tuned below a 2 to 1 vswr without much difficulty. In addition, the phase of most loads will stay put. A 2 to 1 vswr of variable phase is probably the worst load that might be expected in most applications.

The first test I made was load pulling. This measures how much the power output and frequency shift as the load vswr is rotated through all phases. The setup of Fig. 9 is used. The oscillator was connected and the center frequency set by means of the tuning screw.

The slide-screw tuner was initially completely out of the waveguide, so the oscillator load was only the matched waveguide termination. To obtain a 2 to 1 vswr, the slide screw was inserted into the guide until the reflected power indicated by M2 increased to a level 9.5 dB below the forward power indicated by M1. A ratio of forward to reflected power of 9.5 dB corresponds to a 2 to 1 vswr.

The shift in load impedance caused the reading on M1 to change also as the probe was inserted into the line. The idea is to get the 9.5 dB difference with the probe inserted. The initial value of M1 is not of concern, as it will always change as the probe is inserted. I then had a 2 to 1 vswr load on my oscillator. The next step was to move the probe of the slide-screw tuner along the line and record the extremes of power and/or frequency. During these tests, a spectrum analyzer was often used in place of the wavemeter to speed the measurement process, but the wavemeter approach works fine. It just takes longer.

First, I measured the effect of load vswr on the oscillator power output for 5 different Gunn diodes. Three Alpha type DGB 6844C diodes were tested at their normal operating voltage of 8 volts. Then two Microwave Associates type 49508 diodes were tested at 7 volts. Table 1 shows the data for 10 to 10.5 GHz in 100 MHz steps. In my oscillator, the Alpha diodes gave slightly more power output. An average output was obtained of about 25 milliwatts for most Alpha diodes at most frequencies. The average for the MA devices was a bit less, about 15 milliwatts. Diodes could be substituted in the oscillator with no adjustment and the frequency would change only a few MHz. This data was taken with a .320-inch iris installed on the oscillator.

In order to determine the effect of various iris sizes, I next made a set of tests with different iris diameters and used the same diode. Iris sizes of .290, .320, and .380 inches in diameter were tried. The pulling was again tested with a 2 to 1 vswr. I found that the effect was considerable. Table 2 shows the results. Increasing the iris hole size increased the output power by about 2 dB. The effect on the frequency stability and cavity Q (determined from the amount the oscillator can be pulled) was significant. The pulling increased from 21 MHz with the small iris to 80 MHz with the large iris. In addition, the oscillator would not operate below about 10.4 GHz. At the heavy loading caused by the large iris, insufficient negative R was available and the oscillations stopped. This is because the optimum operating frequency for this diode was above 10.5 GHz for the particular dc voltage applied.

The .320-inch diameter turned out to be a good size. High power output and pretty fair stability were obtained. The data indicates how a little rf power can be traded for a lot of frequency stability. For low-power applications such as receiver local oscillators, I would use a small iris. The improvement in frequency stability for varying loads is certainly worth it.

The dc supply voltage may be used to adjust the oscillator frequency slightly. This is a simple way to make an afc system if done carefully. The tuning range is not as great as can be obtained by putting a varactor diode in the cavity, but it is an easy approach. The tuning range is limited by the amount the supply can be changed before the oscillator quits. For small diodes such as those used here, a variation of plus or minus 1 volt from the nominal supply of 7 or 8 volts seemed reasonable. Lower voltage increases the current and power drops. Increased voltage will also drop the power and the oscillator will eventually quit as the electrons are slowed from the optimum transit-time velocity.

I tested the oscillator into a matched load and measured the degree of frequency "pushing" that could be obtained. The smallest iris was used since an afc system would require that the best oscillator load-stability option be used.

The three Alpha diodes were used for this test. I set the cavity to 10.5 GHz with the dc supply at 8 volts. The voltage was then changed plus and minus 1 volt in one-half steps and the frequency shift noted. The data is in Table 3. All diodes behaved the same. The frequency could be shifted down about 15 MHz and upward about 8 MHz. The power variation was only 4 milliwatts out of about 15 milliwatts average. This is quite acceptable for most applications.

After making this test, I began to wonder what effect the load vswr would have on the frequency "pushing" sensitivity of the oscillator. An especially unfortunate change in load could pull the oscillator so far that it could not be returned to the correct frequency by "pushing" with the dc supply. In order to cut down the time to take the data, only a single diode sample was tested. The great similarity of results for the other tests indicates that these results are probably valid for the other diodes. Alpha diode number 1 was used with the .290-inch iris on the cavity output. First, I varied the supply voltage as before and noted the frequency shift obtained with a matched load. Table 4 shows the data. Next, the vswr was increased to 2 to 1 and the frequency was pulled up the band as far as possible (the dc supply was returned to 8 volts during this adjustment). Next, I varied the supply again and noted the frequency relative to the *original* 8-volt center frequency. Finally, the oscillator was pulled down the band as far as possible with the load vswr and the data was taken again.

From the data, it may be seen that the range of adjustment with a matched load is −15 to +8 MHz. With the frequency pulled high with load vswr, the range is −25 to +17 MHz. The oscillator passed through the reference frequency somewhere between 7.0 and 7.5 volts. In this case, the supply could be used to afc the oscillator back to the starting frequency. With the oscillator pulled below the operating frequency, the range of adjustment with the supply was from −25 to −6 MHz. Nowhere in the range of supply-voltage adjustment did the oscillator return to the initial frequency. In this case, an afc loop could not correct the frequency shift due to load pulling. It could only approach within 6 MHz and would "hang up" on the low side as indicated in the fourth column of Table 4.

One other factor is evident from these results. The modulation sensitivity varies a lot as a function of load. For the matched load case, the shift for a 0.5-volt change from 8.5 to 9.0 volts is only 3 MHz. With the oscillator pulled high, the change in frequency as the supply is varied from 7 to 7.5 volts is 30 MHz. With the oscillator pulled low (column 4), the frequency change for the same supply-voltage shift is only 7 MHz.

My conclusion is that an afc or phase-lock system that uses the supply voltage is feasible, but with a few cautions. The load vswr that the oscillator sees should be low if at all possible, and it certainly should be controlled.

If this is not done, the loop may lose range or go unstable. When setting up an afc system, the oscillator should be mechanically tuned to the desired frequency while monitoring the supply voltage so that it may be centered with the loop closed. Because the amount of tuning that can be obtained is so limited, this approach will ensure that all of the range is available to cope with thermal drift. If the load changes significantly, the loop may well lose control.

The real key is to keep the load vswr as low as possible. This will minimize the effect of changes in load phase upon the oscillator frequency.

This concludes the test data I obtained. Hopefully, it is complete enough so that the oscillator may be put to use in your X-band command link or whatever.

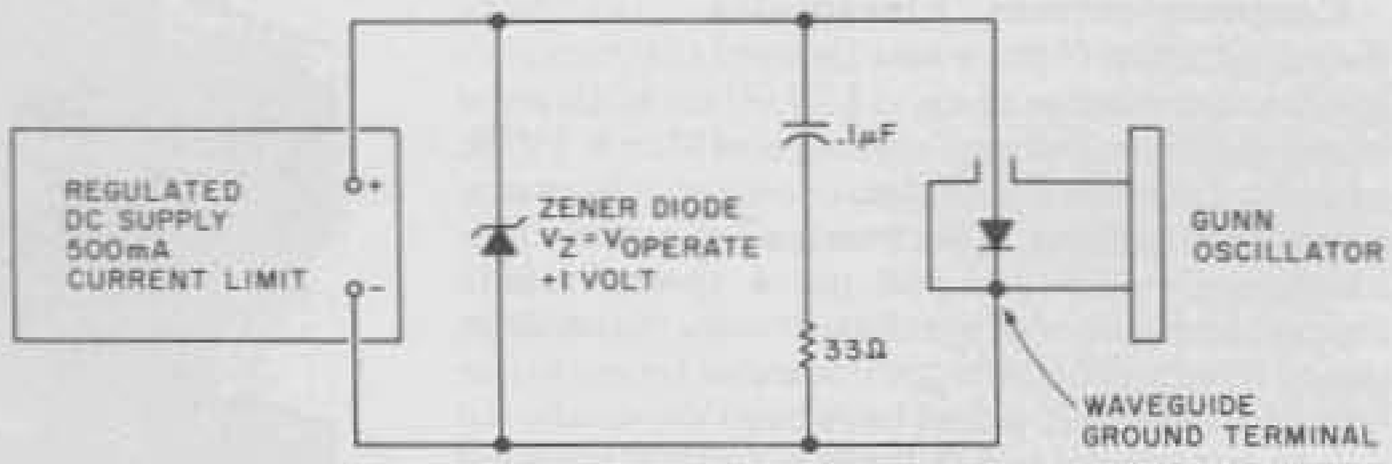


Fig. 8. Dc power-supply circuit for testing Gunn-diode oscillators. The zener-diode voltage should be about 1 volt more than the intended operating voltage for the oscillator.

X-Band Transceiver

I added a simple mixer to the basic oscillator to make an effective X-band transceiver. My application was for Doppler radar, but the device is equally useful for communications. When mated with the Doppler processor described in the next section, the unit will provide positive detection of man-sized targets at ranges up to 100 feet or so.

A number of the commercial Doppler radars used for door openers, speed meters, or intrusion detection use a simple "diode in the guide" mixer for reasons of cost. In this approach, a mixer diode is simply placed in a section of waveguide between the Gunn oscillator and the antenna-mounting flange. No ferrite circulator is used for transmit-receive signal separation. At best, this approach is 6 dB poorer in performance than if a circulator is used, but it is simple to make and works quite well for many applications.

In operation, a portion of the transmitted energy is intercepted by the mixer diode. For communications, this serves as the local oscillator, and in a Doppler system it serves as the zero-velocity frequency reference. The amount of energy that is coupled to the diode must be controlled so that there is something left to radiate. In my design, this was done by offsetting the diode from the centerline of the waveguide. The electric field intensity is maximum at the centerline of the guide and falls off toward

Iris Diameter Inches	Power Output Milliwatts	Frequency Pulling MHz peak to peak	Loaded Q
.290	15 to 32	21	250
.320	22 to 40	40	131
.380	35 to 45	80	65

Table 2. Effect of iris diameter. This table shows the effect of iris diameter upon the power output and frequency stability of the oscillator as the load is varied through all phases of a 2 to 1 vswr. The test frequency was 10.5 GHz. Diode number 3 was used for this test. The oscillator would not operate below 10.4 GHz with the .380-inch iris.

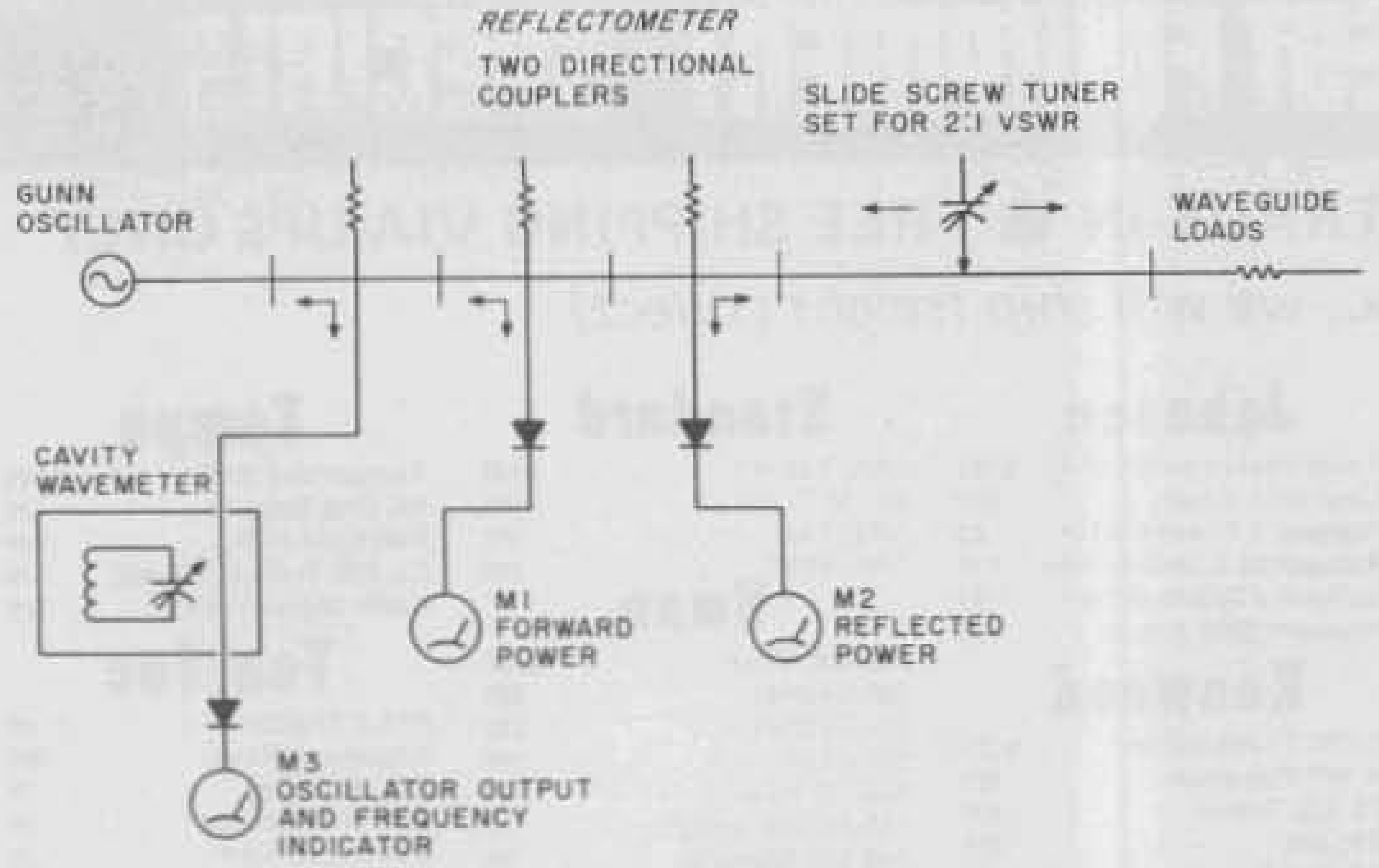


Fig. 9. Schematic of the Gunn-oscillator test setup.

the sides. It is zero at the side walls since they effectively short the field.

I positioned the diode mount 0.250 inches from the outer wall of the waveguide. At this location, about one-half of the energy from the Gunn oscillator is intercepted by the diode. The rest continues down the guide to the antenna.

The iris on the Gunn-oscillator output port is not a perfect short, but it does present a very high vswr to the guide. This is fine for the oscillator coupling because the goal is to mismatch the oscillator so that it is decoupled and the cavity Q remains high. It also effectively shorts the guide behind the mixer diode for energy entering the transceiver from the antenna. The presence of the iris means that the electric field will be maximum about one-quarter wave up the guide from the iris plate because it has to be nearly zero at the iris.

I placed the mixer diode three-quarters of a wavelength from the plate. Since impedances repeat every one-half wave, the three-quarter-wave position is equivalent to the quarter-wave location. This was done to put the diode far enough from the iris for the energy from the oscillator to return to the normal TE_{10} mode pattern. I was concerned that the desired coupling to the diode might be difficult to obtain near the iris and didn't want to spend a lot of time in optimization of the circuit.

The mixer diodes used in my transceiver were chosen because they are in a package similar to the ones housing the Gunn diodes. The same sort of mount is used and all of the pieces are the same with the exception of the post, which is smaller. I purposely avoided the 1N23 type of package because it is hard to mount and a second set of hardware would have to be designed for it.

Dc supply voltage	Diode #1 Freq. Shift	Diode #1 Pout mW	Diode #2 Freq. Shift	Diode #2 Pout mW	Diode #3 Freq. Shift	Diode #3 Pout mW
7.0	−15	14.2	−18	20	−15	19
7.5	−7	14	−10	17	−8	21
8.0	0	14	0	16	0	20
8.5	+5	15	+6	17	+6	19
9.0	+8	15.5	+10	18	+10	17

Table 3. Frequency pushing with supply voltage. This data shows the effect of supply voltage upon the oscillator frequency with a matched load. The iris diameter was .290 inches. The oscillator was tuned to 10.5 GHz with the supply at 8 volts to establish the initial reference frequency.

Diodes in the small (double prong or MQM) package are made by Microwave Associates, Alpha Microwave, and Hewlett-Packard, to name a few vendors. I used the H-P 5082-2711 diode in my transceiver. This is a Schottky barrier type. Other diodes which should work include the Alpha type DMF 6106 and the MA type 40006. These are also Schottky types. A point-contact type which may prove cheaper to buy is the Alpha type D5523C. The point-contact diodes will work as well as the Schottky diodes in most applications. Remember when ordering these diodes to get ahold of a data sheet because they are graded for noise figure. The numbers above I selected for worst noise figure and lowest cost. By changing a suffix or adding one, the noise figure gets better and the price gets worse. No diode listed above has a noise figure of more than 9 dB. You can get 6.5 dB, but boy, it will cost!

Transceiver Construction

Photo F shows the breadboard version of the transceiver. Photo D shows the final version which eliminates the two flanges coupling the oscillator to the mixer. It is mounted upon the Doppler processor box. The integrated version of the transceiver is made from a single section of X-band waveguide. The oscillator section is identical to the separate oscillator circuit just described. All of the internal details are the same with the exception of the coupling iris; it is soldered directly into the guide.

Two flanges are eliminated and a nicer assembly is achieved. To install the iris, first cut through three of the four walls of the waveguide, as indicated in Fig. 10. One broad wall and the two narrow walls are cut. Make up the iris plate from copper or brass sheet somewhat thinner than the saw blade. Install the iris in the saw cut and solder into place. Take some care in this. All four walls of the guide must be soldered to the iris plate on both sides. If not, you will create a truly marvelous slot antenna! Remove all flux after soldering.

The mixer diode is installed in a mount similar to the Gunn-diode mount. The mount parts are as indicated in Fig. 7. The mixer post is made from 0.250-inch rod stock rather than the .312-inch-diameter stock used for the Gunn diode. The mixer-mount parts are assembled into the guide in exactly the same manner as the Gunn-diode mount. There is one difference. No heat-sink goo is required for the mixer diode. Hole A on the mixer side of the iris is for a ground lug to return the mixer load resistor to the guide. This resistor is used to prevent static burnout of the mixer diode during initial testing.

In assembling the transceiver, first cut the guide to length and then drill and deburr all holes. Tap holes as required. Make the saw cut and install the iris. Solder the output flange to the mixer section as indicated in Fig. 10. Use a large C-clamp to heat sink the iris area when installing the output flange. This will prevent the solder holding the iris plate from running. Remove all flux. The two diode mounts may be installed next. Then install the shorting block with lossy probe in the end of the oscillator cavity. Install the tuning screw. Install the Gunn diode. Connect a 5k resistor from the mixer-diode output terminal to the ground lug. Now install the mixer diode using care not to damage it with static. Pick up the transceiver body with one hand while holding the diode in the other. This will put the transceiver and the diode at the same potential. Then install the diode in the transceiver. The Gunn diode is more rugged and may be handled normally, so these cautions do not apply to it. In my version of the Doppler radar, I located the .1 μF capacitor and 33-Ohm resistor components of the Gunn-diode dc supply circuit on a small tie strip. This tie strip is mounted to the waveguide by the same screw that holds the shorting block in place. These parts are visible in the photo.

The transceiver is now ready to be tested.

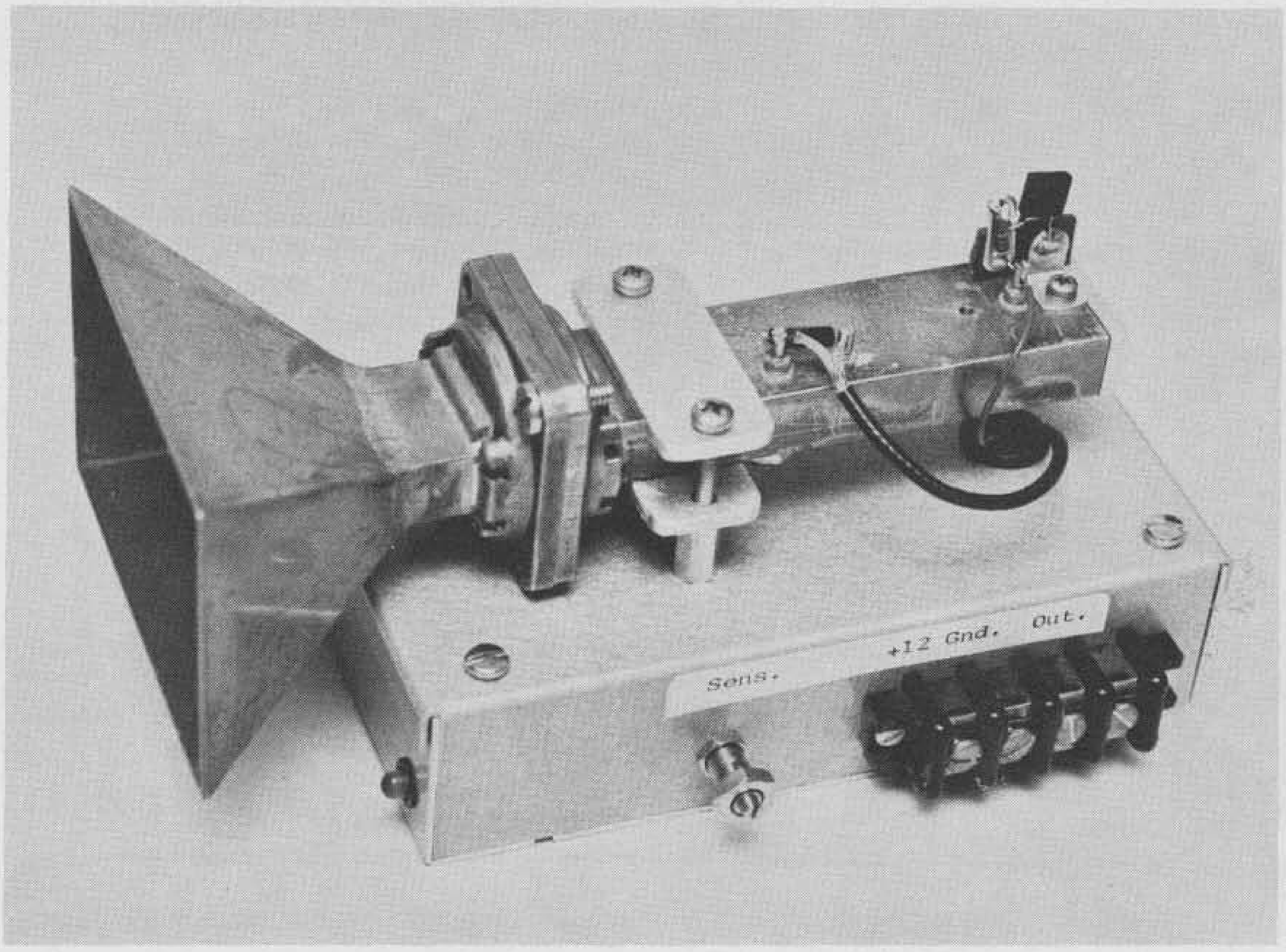


Photo D. The Doppler radar assembly. The final version of the X-band transceiver is mounted to a box which contains the Doppler processor to form a self-contained Doppler radar. The 10k-diode load resistor may be seen to the rear of the coax cable which connects the mixer output to the processor card. The 33-Ohm resistor and 0.1 μF capacitor are mounted on the small terminal strip and connected to the Gunn-oscillator dc input terminal. The 2-56 cavity frequency adjustment screw is not installed in this photo. One of the two LEDs used for adjustment is visible under the horn antenna.

Transceiver Test

Arrange a power supply for the Gunn diode as described previously. Apply power and test for supply stability with a scope. If everything is okay, the oscillator should be operating. Connect a voltmeter (20,000 Ohms/volt) to the mixer-diode output. Do this with care. Ground both meter leads to the waveguide and then connect the positive lead to the diode output. The diode should be rectifying some of the rf energy and a voltage of a few tenths of a volt will be present. If the diode voltage is negative with respect to ground, the diode is in backwards. This is of no concern in most applications.

If no voltage is measured, there are three possibilities: The diode is no good, the Gunn is going at 13 GHz and no power is coming out of the oscillator, or perhaps the tuning screw is in too far and is shorting the cavity. First, back out the tuning screw until it is out of the guide. Next, try another mixer diode. If this doesn't help, remove the shorting block from the cavity and verify the pencil-lead probe insertion. If it is okay, then make sure that it is soft pencil lead, which has more carbon in it. Reassemble the oscillator without the probe. Set up as before and apply power. Observe the voltmeter on the mixer diode and slowly insert the lossy pencil-lead probe into the cavity through the hole in the shorting block. If a diode-mount oscillation was the problem, the mixer diode will suddenly indicate the presence of rf when the probe kills the spurious oscillation.

Once things are going, some interesting tests can be made. The open waveguide flange is not a bad antenna. The gain is about 5 dB! Point the business end of the transceiver out into the room and connect a scope across the mixer-diode output. With the scope gain at 10 to 100 millivolts per division and ac coupling, the Doppler shift on moving people is quite readily seen. Adding a good antenna will greatly increase the return. Hooking the mixer output into a hi-fi amplifier with a good low-frequency speaker is also entertaining. People, fans, and cars make really strange Doppler noises.

If you build two transceivers or an oscillator and transceiver, the following test is interesting. Set them up about 6 feet apart with the waveguides pointed at each other. Observe the mixer output of one unit on a scope while tuning it across the frequency of the other. The diode-mount capacitance measures about 13 pF, so a bandwidth from dc to several megacycles is obtained without tuning the mount at i-f. As the frequency of one unit approaches that of the other, the beat may be seen on the scope. This is the i-f frequency created by mixing the two X-band signals. As the frequencies are brought closer, the beat frequency drops and then it will suddenly vanish. This happened at about one MHz with my units. At first this seems strange, since the mixer mount will work down to a dc i-f frequency.

The answer is that the two oscillators have locked together and are now on the same frequency. Further tuning will eventually pull them apart. This is an example of injection phase locking. In some high-power sources, injection locking is used to obtain more power than a single diode will supply by locking several units together. As you can see, not much power needs to be injected to lock one to another.

Communications

The transceiver may be used for communications.

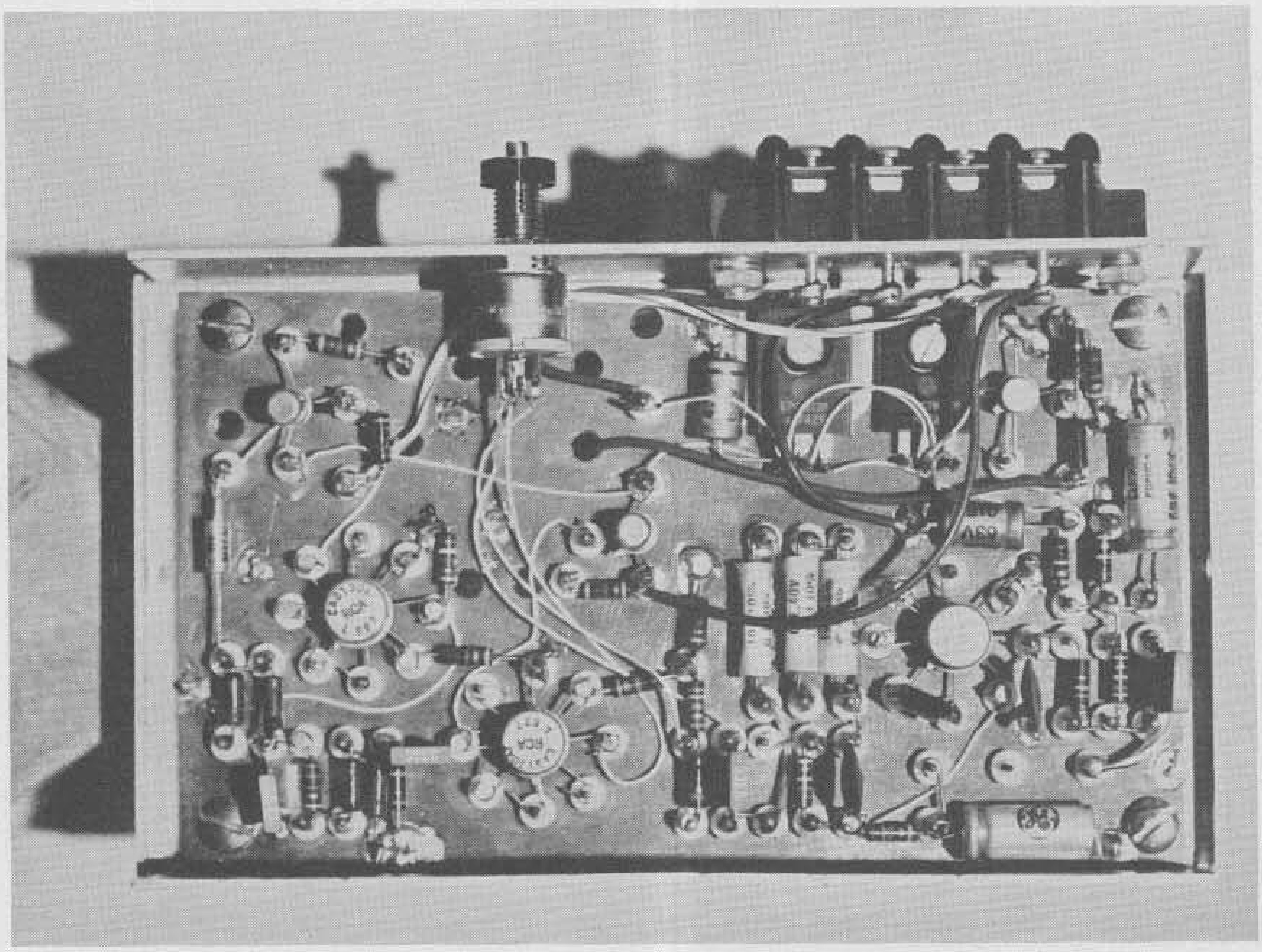


Photo E. The Doppler processor card. Signal flow is from right to left across the bottom of the card. U1 is located at the lower right, U2 in the center, and U3 at the left of the card. The analog pulse-counter circuitry is in the lower left-hand side of the card below U3. The voltage-regulator circuits are at the upper right near the input/output terminal block.

An FM tuner makes a good i-f strip for getting started. Most of the tuners have a pretty fair noise figure, but getting a proper match to the mixer is also important if good results are to be achieved. Most modern microwave receivers solve this problem by putting a preamplifier right at the mixer. I recommend doing the same. A good low-noise dual-gate FET preamplifier will overcome any deficiencies of the FM radio and will enable the mixer to be matched to a well-controlled amplifier input impedance. The preamplifier can then drive a cable to the receiver.

The i-f impedance of the mixer will be a function of the diode current and will be from 200 to 500 Ohms. The diode mount has a capacitance of about 13 pF. This should be tuned out with an inductor which also serves as the dc return for the diode, as in Fig. 11. The inductor and diode-holder capacitance should be resonant at the i-f frequency. The resulting real impedance is then matched into the preamplifier.

FM modulation of the Gunn diode is simply a matter of modulation of the power-supply voltage. Be sure to limit the peak-to-peak excursion of the supply to prevent damage to the diode. A good modulator approach would be to ac couple the audio into the reference source for the dc regulator. This will offset the reference and force the dc voltage from the supply to follow the audio. The supply must be capable of moving at audio rates. This means that giant filter capacitors on the output cannot be used. In addition, some form of modulation limiting should be provided so that deviation is controlled. Remember, the oscillator can be deviated several MHz per volt of supply change. If a standard FM radio is used as your i-f strip, only 75 kHz of peak deviation is needed. So only a few hundred millivolts of audio are required on the dc supply.

The communications range that you can get with this transceiver is very much dependent upon the antennas used. The noise figure is fairly decent, and, with a 200 kHz bandwidth FM tuner for an i-f strip, sensitivities of −100 dBm or so should be obtained. The path loss at 10 GHz for 10 miles is 136 dB.

As an example, consider the use of a pair of 20 dB gain horns and about 10 milliwatts of power. The power at the receiver mixer and output carrier-to-noise ratio are:

Transmitter output:	+10 dBm
Transmitter antenna gain:	+20 dB
Receiver antenna gain:	+20 dB
Path loss (10 GHz & 10 miles):	−136 dB
Power at the receiver mixer:	−86 dBm
Sensitivity:	−100 dBm
Output carrier-to-noise ratio:	+14 dB

The actual signal-to-noise ratio will be somewhat better because of the FM improvement resulting from the high modulation index if the full 75 kHz deviation is used. By going to a pair of 3-foot dish antennas, a gain of about 36 dB is obtained. This will improve each end of the link by 16 dB for a total gain in SNR of 32 dB over the case above. Of course, the improved SNR can be traded for greater range at the rate of an additional 6 dB of loss for each doubling of the distance.

Doppler Processor

The X-band transceiver may be used as an effective Doppler radar for protecting the goodies in your ham shack from burglars by adding the Doppler processor section described next. Doppler radars respond only to moving reflectors, and, if properly employed, can provide nearly foolproof protection against intruders. The trick is to achieve a very low false-alarm rate so the circuit is not continually "crying wolf."

The Doppler effect refers to an apparent shift in the frequency of a radio signal which occurs if the transmitter is moving relative to the receiver. The amount of frequency offset that occurs is determined by both the transmitter frequency and the velocity of the transmitter relative to the receiver. The frequency shift is given by the simple formula: $F = f_o \times V/C$. F is the shift. f_o is the transmitter frequency. V is the velocity difference and C is the speed of light. The frequencies are in Hz and the velocities in meters per second. In the radar case, the signal experiences the Doppler effect in both directions of propagation, to and from the target. Here, the resulting shift is doubled from the values given by the formula.

The Doppler effect is used in a variety of radar applications where measurement of speed or separation of moving from stationary targets is desired. The police speed meters are one example, of course, but others include air search radars which use Doppler to reject ground clutter (ground doesn't move) and accept airplanes (which always move).

If an intrusion-detection radar operates at 10 GHz, the maximum Doppler shift obtained with a walking person as a target is about 40 Hz. The lower end of the Doppler range extends to very low frequencies. I used 4 Hz as the lower band edge of the processor after observing the Doppler output of the transceiver on a scope and determining that there is a lot of energy near dc; some of us don't move all that fast! In any event, the 4-40 Hz processing bandwidth seems to work well in practice.

The objective in the processor design is to obtain positive target detection with a low false-alarm rate. The circuit has to have some "smarts" so that it does not trip on the first cycle or two of 4-40 Hz audio to come out of the Doppler mixer. In order to obtain an alarm output, the processor requires that a large number of cycles of Doppler occur within a relatively short span of time and that more recent events be given greater weight than those which occurred many seconds earlier. This feature prevents noise from causing single-event false alarms, and, as a consequence, the circuit almost never produces a false output. An alarm output on a real person is obtained in about 2 seconds.

The processor has four major sections: an input preamplifier, a squaring amplifier, a pulse counter, and an output threshold detector. It also contains a power supply for the processing circuits and a regulator for the Gunn-diode oscillator. Two LED indicators are provided to aid in setting the circuit sensitivity. One blinks when Doppler is present; the other indicates an alarm-decision output. Fig. 12 is a schematic diagram of the circuit.

The input preamplifier has a 4-40 Hz bandpass which is obtained by RC rolloffs in the input and feedback networks. The op amp, U1, is an RCA type CA 3130 FET input op amp. I used this part in all three stages of the processor because it has a number of advantages for this type of circuit. The high-input impedance permits good low-frequency response with small (0.1 μF) capacitors. If a 741-type amplifier were used, some truly huge values would be required to obtain response to 4 Hz. The FET input stages also permit the CA 3130 to run from a single-ended supply with the common-mode input voltage at the inputs as much as one-half volt below ground. This was handy in the last stage. Finally, the output section of this chip is a CMOS inverter used as an amplifier. This permits the output to swing within 50 millivolts or so of the supply voltages. Thus the circuit will interface directly with CMOS and, in the case of the squaring amplifier stage, will provide an output swing equal to the supply voltage. This saved some parts.

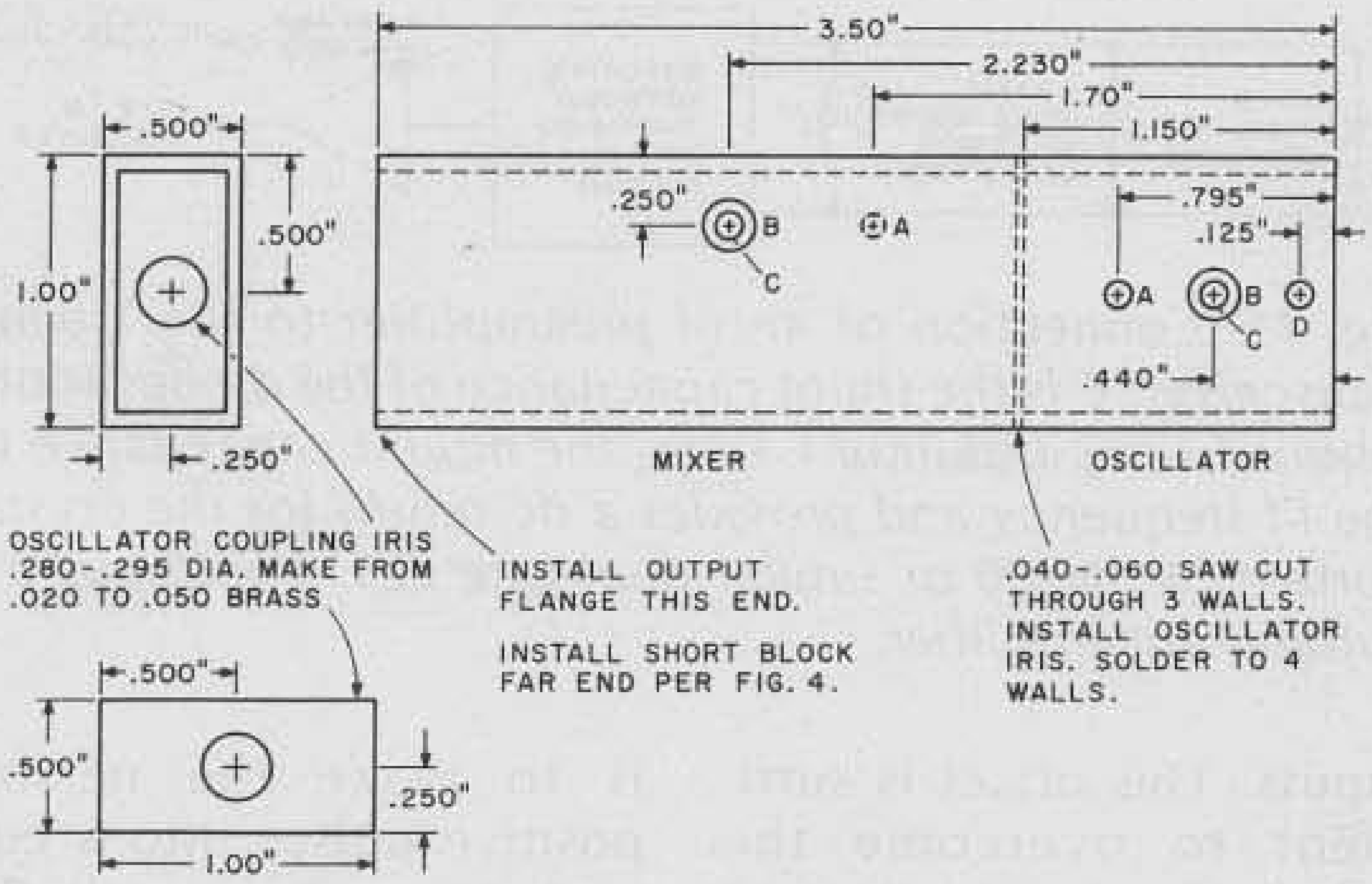


Fig. 10. X-band transceiver waveguide. The function and size of the lettered holes are the same as in the table in Fig. 6.

The noninverting input of U1 is biased at +5 volts by the voltage divider, R3 and R4. Input capacitor C1 and resistor R1 form a high-pass filter with a 4-Hz corner frequency. R2 and C2 form a 40-Hz low pass. The amplifier gain is set to 60 dB by feedback resistors R5 and R6. Capacitor C5 is used to obtain a 40-Hz high-pass rolloff in the feedback network. The 68 microfarad capacitor, C4, in conjunction with R6, causes the gain to decrease below 4 Hz. The amplifier gain is unity at dc so the output sits at the input bias point of +5 volts in the absence of an input signal. High-frequency compensation of the preamplifier requires a 100 pF capacitor from pin 1 to pin 8 as indicated.

The second stage of the processor, U2, also uses the CA 3130. Positive feedback around the amplifier is employed to obtain a squaring amplifier. The objective is to turn the complex sine-wave Doppler audio into a series of 10-volt peak-to-peak square waves. The input circuit of U2 is a bit novel and requires some explanation. The voltage divider consisting of R7, R8, and R9 forms the reference for both the inverting and noninverting inputs. This reference voltage is about 5 volts. The 6.8-Ohm resistor, R8, ensures that the voltage at the inverting input is always about 34 millivolts more positive than the noninverting input. In the absence of an audio input signal (which is ac coupled), the op amp is always driven to ground potential because of the intentional 34 millivolt offset introduced between the inverting and noninverting

Dc supply voltage Volts	Frequency shift matched load vswr 1.1 to 1	Frequency shift osc. pulled high with 2 to 1 vswr	Frequency shift osc. pulled low with 2 to 1 vswr
7.0	−15 MHz	−25 MHz	−25 MHz
7.5	−7 MHz	+5 MHz	−18 MHz
8.0	0 MHz	+10 MHz	−14 MHz
8.5	+5 MHz	+13 MHz	−7 MHz
9.0	+8 MHz	+17 MHz	−6 MHz

Table 4. Effect of load vswr on frequency pushing. This table indicates the effect of load vswr upon the center frequency and tuning sensitivity of the oscillator. Note that when the frequency was pulled low, the initial frequency could not be restored with supply voltage. Diode number 1 was used with a .290-inch diameter iris.

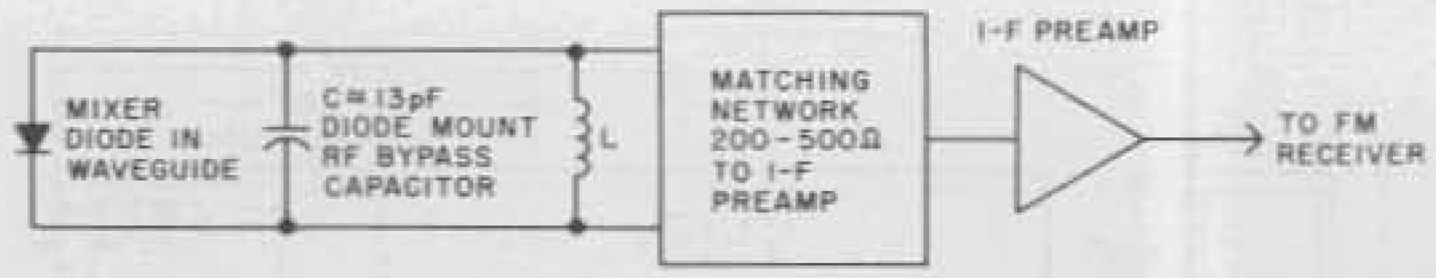


Fig. 11. Connection of an i-f preamplifier to the X-band transceiver. C is the shunt capacitance of the diode mount (about 13 pF). Inductor L tunes the mount capacitance to the i-f frequency and provides a dc return for the crystal current. A 3N200 or similar dual-gate FET would make a suitable preamplifier.

inputs. This offset is sufficient to overcome the worst case input offset of the op amp and ensures that the output voltage always swings to ground. This is done so that the LED driver, Q1, is normally off.

The particular configuration used was chosen because it is independent of both supply-voltage and resistor variations. No precision parts are required.

The Doppler signal is coupled into the squaring amplifier input from the preamplifier stage via capacitor C6 and gain control R10. When R10 is set to full gain, less than 50 millivolts of Doppler at the input to the squaring amplifier is sufficient to obtain a 10-volt peak-to-peak square wave output from U2. The presence of Doppler causes LED −1 to flash at the Doppler rate.

The circuitry following U2 is the heart of the processor. It is here that the low false-alarm rate is obtained. In effect, the circuit is an analog pulse counter with a short memory. The first section, consisting of C7, R13, and CR1, is a rectifying differentiator. It converts the square waves from U2 into a series of short positive-going pulses. The shunt diode rectifier clips all negative-going edges so only the positive pulses remain.

These positive pulses charge C8 through R14. The series 1N914, CR2, prevents the accumulated charge from discharging back through R13 to ground. The effect of R14 is to make the narrow positive pulses into a current source. As a result, the voltage accumulated in C8 is a function of the number of input pulses. The circuit is essentially a pulse counter with an analog voltage output.

This approach is simpler and cheaper than a digital counter and can be made to "forget" at any rate desired. The objective is to have the circuit slowly reset itself if an insufficient number of pulses are counted. This is a way to give more recent events more weight in determining if there is an intruder present. Two groups of pulses separated by a short interval in time should set off the alarm. Similar groups spaced widely apart in time (several minutes apart) should not. The "forget-it" function is obtained by R17, which slowly discharges C8. Adjustment of R17 allows the circuit to have any memory time required.

The output of the analog pulse counter is applied to U3, another CA 3130 op amp. U3 functions as both a high-impedance comparator and as a one-shot multivibrator. The inverting input of the amplifier is referenced to +2 volts by R15 and R16. The voltage from the analog pulse counter is applied to the noninverting input. When this voltage is less than +2 volts, the output of U3 is 0 volts. When the input exceeds +2 volts, the output of the CA 3130 goes to +10 volts and the circuit becomes a one-shot.

The one-shot functions as follows: C9 is initially discharged via CR4. CR3 is reverse biased, which effectively disconnects C9 from the input to U3. Thus, the only capacitor in the pulse counter circuit is C8. When the output of the CA 3130 goes to +10 volts, CR3 becomes forward biased, and since C9 is essentially discharged, the voltage at the noninverting input of U3 is nearly 10 volts. This positive feedback holds the output of U3 at +10 volts. C9 starts to charge through R17 and the voltage at the noninverting input falls toward ground at a rate determined by the R17 and C9 time constant. C8 is also in the act, but to a lesser extent because of its lower capacitance relative to C9. Eventually, the voltage at pin 3 drops below +2 volts and the circuit resets. The output voltage from U3 then returns to ground potential. The output pulse width is more than one second with the values shown. The arrangement of the circuit is convenient in that longer pulse widths may be obtained by increasing the value of C9 without any effect upon the analog pulse counter. In one version of the circuit, the output pulse width was increased to 3 minutes by increasing C9 to about 60 μF. In this application, the output pulse operated an alarm circuit directly for a 3-minute interval.

The LED drivers, Q1 and Q2, are 2N2222 or similar NPN transistors connected as emitter followers. Just about any LED will work. I used the high-efficiency HP 5082-4650 types which make a lot of light from only 10 mA of current. If lower-efficiency LEDs are used, the 820-Ohm resistors, R18 and R19, may be reduced in value to obtain more current. Note that the LED driver collectors are returned to the unregulated +12-volt line and not to the +10-volt regulated supply. This is intentional. The current pulses created by the LED drivers could get back into the low-level input stages and cause an oscillation via the +10 supply line. By using the connection indicated, the voltage regulator isolates the low-level stages from these current pulses.

The Doppler processor operates from a nominal 12- to 15-volt dc input. Higher voltages can be used if the heat sinking of the supply regulators is improved. A 10-volt supply was chosen for the op amps to ensure sufficient "overhead" to maintain the voltage regulator in regulation. The CA 3130s require at least 8.5 volts to really work well. The regulator for the Gunn-diode oscillator supplies +7 volts and is compatible with the Microwave Associates Gunn diodes. The 8-volt Alpha parts will also work from this voltage.

The regulator circuit was designed to supply the 7- and 10-volt requirements using standard 5- and 8-volt 3-terminal regulators of the MC7800 series. Seven volts is obtained by offsetting the common terminal of U4, a MC7805 CP, 2 volts above ground. This is accomplished with emitter follower Q3, which has its base referenced to a divided sample of the 7-volt regulator output. The sample is derived from divider R22-R24. Resistor R24 is a select in test value and is used to adjust the circuit to exactly 7 volts of output. The divider cannot be fixed because of the wide output-voltage tolerance of U4 and the variations of V_{be} of Q3. The +10-volt regulator is made by referencing the common terminal of an 8-volt three-terminal regulator chip to the +2-volt source at the emitter of Q3. The current from the common terminal to ground for both chips runs through Q3. An emitter follower was used rather than a simple resistive divider to provide a low-impedance constant voltage sink for this current and to avoid the necessity for high-dissipation low-value resistors in the voltage-divider network.

Doppler Radar Construction

The complete Doppler radar is packaged in a 5.5" x 1.5" x 3.0" minibox as indicated in the photos. The X-band transceiver is mounted to the top exterior surface of the box with a clamp which grips the waveguide. The Doppler processor card is mounted inside the box and attached to the same surface as the waveguide. The card is mounted with number 6 screws and spacers. This arrangement makes it possible to remove the bottom cover for test or servicing without disturbing any wiring. The sensitivity control and input/output terminal strip are mounted on one side of the box. The LED indicators were mounted on one end of the bottom cover and connected to the circuit card with long leads to permit easy removal of the cover.

The Doppler processor card is constructed using copperclad PC board and push-in standoff terminals. Wiring is all point-to-point. There is no particular magic in the layout except to keep the signal flow in one direction. The circuit does have a lot of gain, but no difficulty with oscillation was encountered. Just keep the output portions of the circuit from being routed near the preamplifier input. Signal flow is from right to left in the photo of the circuit card. U1 is in the lower right-hand corner of the card and U3 is in the lower left-hand corner. The three large parts to the left of U1 are capacitors for a 120-Hz notch filter that was deleted from the circuit. They are not required and are not indicated on the processor schematic. The voltage regulator chips, U3 and U4, are mounted to the circuit card. This arrangement provides sufficient heat sinking for the power dissipated at input voltages up to 15 volts.

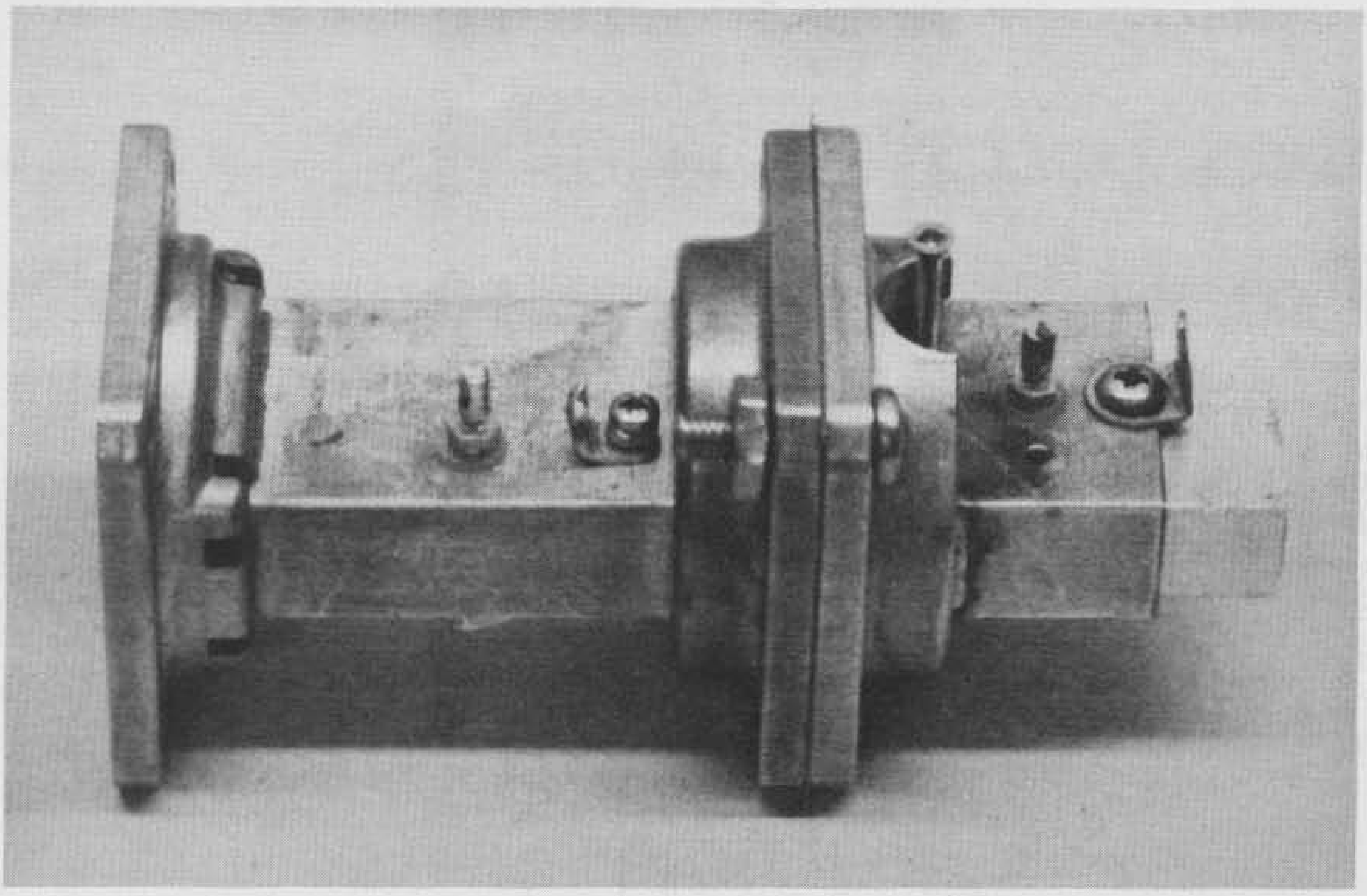


Photo F. X-band transceiver breadboard. The X-band transceiver was developed by adding a simple "diode in the guide" mixer assembly to the breadboard oscillator. The coupling iris is clamped between the mating waveguide flanges.

The output from the Doppler mixer is connected to the processor input at terminals T5 and T6. Shielded cable is used to prevent noise pickup. The mixer diode on the X-band transceiver has an output terminal and a ground terminal. A 10k resistor should be connected from the output terminal to ground. This serves two purposes: It provides a dc return for the Doppler mixer and it serves to ensure discharge of the coupling capacitor, C1, in the Doppler-processor preamplifier. The output terminal of the mixer is connected to input terminal T5 on the processor via the shielded center conductor of the input cable. The ground terminal on the mixer is connected to T6 on the processor with the coax cable braid.

The connections to the mixer from the preamplifier should be made prior to final installation of the mixer diode. This is done to reduce the danger of diode burnout during the soldering operation.

The Gunn-diode oscillator portion of the X-band transceiver is powered from terminal T7, the 7-volt output of the processor voltage regulator.

Doppler Radar Operation and Test

Some initial testing of the Doppler processor may be performed independently of the X-band circuitry. This is useful to isolate any problems with the processor.

After checking the wiring, apply 12 to 15 volts dc to the processor supply input terminal, T3. Load the +7-volt regulator with a 50-Ohm, 1-Watt resistor. This will draw 140 mA from the oscillator supply and will simulate the Gunn-oscillator load. Measure the +7-volt regulator output. It will not be exactly 7 volts. Adjust the select in test resistor, R24, to obtain 7 volts within a tolerance of plus or minus 250 millivolts. The voltage at the output of the +10-volt regulator should be checked and will be pretty close. 9.5 to 10.5 volts is acceptable. Voltages less than 9.5 will cause performance of the op amps to degrade. If all is well, the voltage at the emitter of Q3 will be just about 2 volts. If this is the case and the 10-volt supply is wrong or inoperative, the problem is with U3. If both supplies are wrong, the problem is with U4 and Q3.

Once the dc supply is operating, the rest of the circuit may be tested. When power is first applied, the large capacitors, C3 and C4, must charge. U1 will be inoperative for about 20 seconds, so do not worry if things don't work immediately after power-up.

Apply a 20-Hz audio signal to the preamplifier input. Use plenty of attenua-

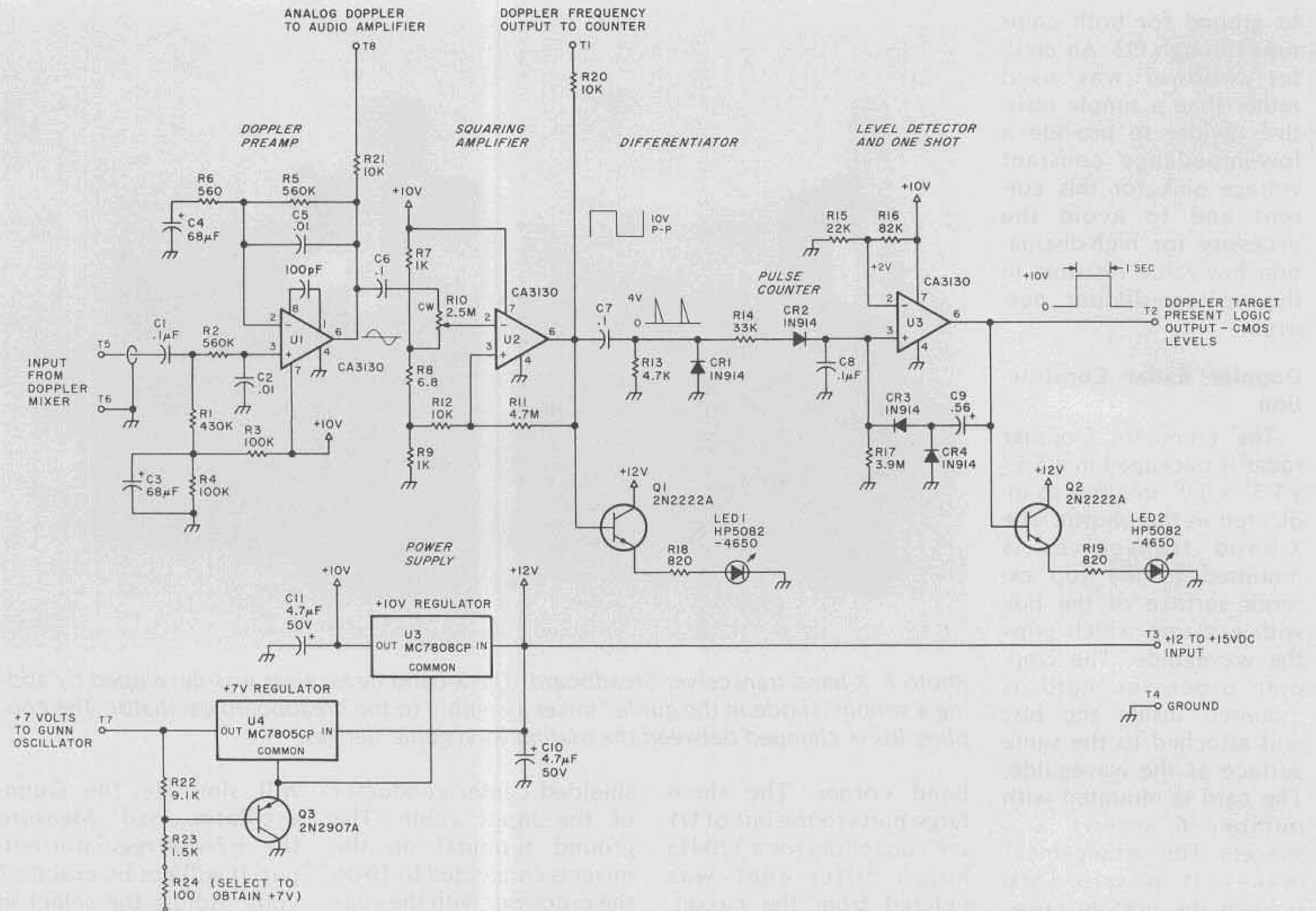


Fig. 12. Doppler-signal processor schematic. This circuit provides a 10-volt CMOS-compatible logic output when a Doppler return is received. The output stage will provide up to 2 mA of output current to an external load.

tion. 50 or 100 microvolts rms should be sufficient. U1 has a gain of 1000 (60 dB) and will easily provide the 50 millivolts of input required to drive U2 to full output.

Increase the input to U1 until 50-100 millivolts is obtained at test point T8. Set R10 for maximum sensitivity and check for a square wave at terminal T1. The amplitude should be 10 volts peak-to-peak.

At this point, LED indicator 1 should be illuminated. Removal of the audio input or a decrease in gain adjustment will cause the LED to go out. If it remains on, check to see if pin 6 of U2 has returned to ground. If pin 6 is at +10 volts instead of ground, then there is a problem in the input bias/offset circuit of U2.

With the square wave present at T1, a series of sharp pulses should be observed at the junction of C7 and CR1. The pulses should be positive-going and have an amplitude of several volts. The pulse will be in phase with the positive edge of the squaring-amplifier output. A small negative-going pulse will occur in phase with the falling edge of the square wave, but will be clamped to −0.8 volts by CR1.

If all of this is working, then U3 will have decided that a target is present and will have a +10-volt output at T2.

Remove the audio input. T2 should go low in a few seconds. Apply the audio input. T2 will go high in about 2 seconds. If the voltage at pin 3 of U3 is observed on a scope or very high impedance meter, it will be seen to rise slowly upon application of audio input. If the input is removed prior to reaching the +2-volt threshold, it will be seen to decay as R17 discharges C8.

If the 2-volt threshold is reached, the monostable trips and the voltage at pin 3 will jump up to nearly 8 volts as the positive feedback is coupled from C9 via CR3.

LED 2 should be illuminated whenever a signal has been applied for more than 2 seconds.

Upon completion of testing, the processor may be operated with the X-band transceiver. When first connecting the transceiver to the processor, be sure to observe the cautions with regard to connection of the mixer diode. Do ensure that C1 is discharged and make the mixer-diode connections with the diode removed from the mount or with the mount shorted. Also, be sure to check for oscillation of the Gunn-diode supply regulator. I encountered no difficulty as long as the .1 μF capacitor and 33-Ohm resistor oscillation suppression network was used at the Gunn-oscillator power terminals.

Place the unit in operation and connect a scope to T8 and a dc VTVM to pin 3 of U3. Walk in front of the waveguide output and observe the Doppler waveform on the scope. The dc voltmeter will indicate the charge and discharge of the pulse-counter circuit. LED 1 will blink whenever there is motion and LED 2 will be illuminated when enough Doppler cycles have been counted to give an alarm indication.

For these tests, the open-ended waveguide is sufficient antenna. The gain is about 5 dB. A range of 10 feet or so will be obtained with this antenna.

The Doppler frequency may be counted by connecting a frequency counter to T1. Use a gate time of one second. The count accumulated will be the total number of Doppler cycles averaged over the one-second interval. Observation of the scope will confirm that the Doppler waveform is complex and is not a single frequency.

The processor output is a CMOS-compatible logic level that goes from 0 to +10 volts when a target is detected. In my application, CMOS logic was used to process inputs from a number of sensors. The output may also be interfaced directly with other devices. The CA 3130 output stage will source or sink 5 milliamperes, which is sufficient to drive an output buffer or relay driver for higher current loads. Fig. 13 is a suggested buffer for loads of up to 2 Amperes.

If the radar is to be used as an intrusion detector, set it up for a couple of weeks in the intended location. Connect an electromechanical counter to the output to record false alarms. This will permit optimization of the sensitivity setting and installation without creating a lot of bothersome false alarms. The circuit has plenty of sensitivity and will see a person at up to 100 feet with a 20 dB gain antenna.

Avoid installations which look directly at a street. Autos have a large radar cross section (as most of us know by now) and are detected at a greater distance than people. What you definitely do not need is a noisy device which informs you that your neighbor is backing out his car!

The unit may be installed in a wood cabinet and will work right through materials such as one-quarter-inch paneling or plywood. Wallboard and plaster attenuate the signal and tend to mitigate the effects of passing autos if the unit is properly positioned.

Antennas

I use a small horn having a length of 2.5 inches and an aperture of 2.3 and 3.0 inches. This is not an especially good horn design from a sidelobe standpoint, but it serves the purpose. Horns are easy to make and have the advantage that their gain and beamwidth are easily calculated. You can make a horn which will almost exactly cover the area to be protected.

Conclusion

In writing this article, I have tried to inspire interest in X-band microwave projects at several levels. The theory of Gunn-oscillator operation and a basic oscillator design are there for those who want the "how-to" information to build one into a communication system of their own design.

The X-band transceiver presented is far from an optimal gadget (especially in terms of noise figure), but it does provide a simple and inexpensive vehicle for experimentation in both X-band communications and Doppler radar. I would like to see someone mount two transceivers at the focus of a pair of 3-foot dishes and have a QSO or two. A number of years ago, a friend sent fast-scan TV over a 1000-foot path using a similar arrangement. By adding attenuators at the receiver, a 10-mile path was simulated with good results. X-band offers plenty of opportunity for TV experiments and for truly secure command links for repeaters.

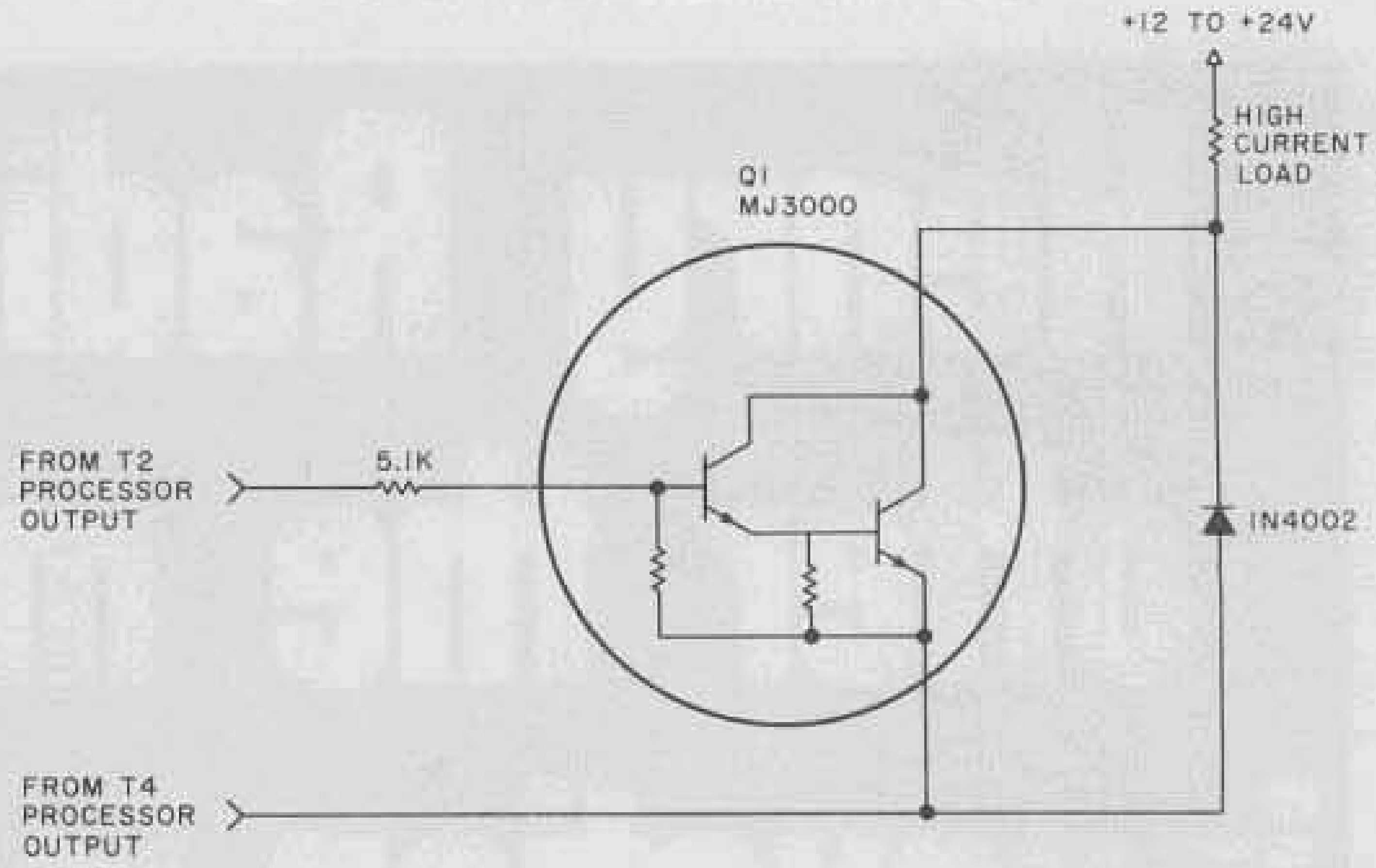


Fig. 13. High-current driver. This circuit uses a high-current Darlington power transistor (Motorola MJ 3000) and will boost the output capability of the Doppler processor such that loads up to 2 Amps at 24 volts may be driven. The diode is to prevent inductive kickback damage to the transistor if inductive loads are connected. The two unlabeled resistors are included on the monolithic Darlington chip.

Doppler radars are interesting projects in themselves. The Doppler processor presented in this article is a practical design I developed to deal with real intruders. Two such units have been in operation for several years with satisfactory results. I am sure that someone will find other uses for this handy form of motion detection.

This article would not be complete without a word with regard to the "radiation hazard." Much has been written of late which alleges a "microwave radiation hazard." A lot of this is uninformed speculation. It has been known for years that microwaves (and lower-frequency rf) cause heating of tissue and that high-power sources such as radars are hazardous.

A major difficulty occurs in attempting to extrapolate the observations for short exposure to high-power sources to long exposure to low-power sources. At present, the permissible level for *continuous* exposure to microwaves or low-frequency rf is not known. Certain standards have been proposed (10, 1, or 0.1 milliwatts/sq. cm) in an attempt to be super safe until more data is accumulated.

Conservative standards are one thing. The real question is this: What precautions should be observed in amateur microwave activities? I apply the same rules that I have used and observed as a working microwave engineer in industry for the past 15 years. They apply equally to microwave projects as to your 2 meter kilowatt. Do not stay in situations of high-power density for long periods. Do not stare into the output of a waveguide source for any period of time at short distances. The level falls off rapidly with distance and is negligible beyond several inches for low-power X-band sources. Remember that a high-power VHF transmitter is equally hazardous if you insist in holding the antenna or standing within a wavelength of it. Time is also a factor. The low-power density recommendations assume exposure on a continuous basis. This is seldom the case in a hobby activity. In short, use common sense.

I hope that this article has provided a starting point for some interesting projects. I will look forward to hearing from anyone who either builds the equipment or who has further questions. ■