Fig. 19 is a picture of the unassembled coupler. It was found that the wall thickness was quite critical in obtaining a precise value of coupling. This is understandable. Fig. 20 is a plot of the wall thickness term in (6). For the holes used in the coupler, change in t of 0.001 inch gives a change of coupling of approximately 1 db.

Results obtained with these couplers over a five-per cent band are typically:

coupling variation	9.8–10.1 db
directivity	greater than 25 db
VSWR, circular guide	less than 1.05
VSWR, rectangular guide	less than 1.15.

The mode purity of the wave passing through the coupler was negligibly disturbed by the coupling holes.

Conclusion

Although care must be exercised in maintaining mode purity it appears feasible to construct many components to operate in the circular electric TE_{01} mode. Test and operational systems operating entirely in this mode in millimeter region appear a possibility for the near future. Major components still lacking are nonreciprocal ferrite devices on which some research has been carried out, and detectors of various kinds.

A Range of 2 and 1 Millimeter Waveguide Components*

R. MEREDITH† AND G. H. PREECE†

Summary—A variety of components have been made in waveguides RG136 and RG139 by techniques which include the use of extruded waveguide, copper-gold eutectic bonding, precision milling and, in particular, of electroforming. Performances of several RG136 components are given, together with the loss in RG139 waveguide and in oversized guide tapered from RG139.

Ferrite devices, including isolators, 3 port switches and amplitude modulators, using Ferramic R1, have been quite successful. A typical isolator has an insertion loss of $1\frac{1}{4}$ db and an isolation of 30 db, magnetically tunable over at least 133 to 145 Gc.

An RG136 slotted line, at a coupling ratio of 20 db, has an inherent mismatch of 1.05 with good reproducibility over the $2\frac{1}{2}$ wavelengths traverse of the one-mil Wollaston wire probe. The main waveguide is milled and broached from brass and gold plated.

Electroformed matched hybrid Tees in RG136 split power to $\pm\frac{1}{4}$ db, have a discrimination of 30 db, a loss of $1\frac{1}{4}$ db and a match looking into any arm of better than 1.4.

Rotary and flap-type attenuators, phase shifters, variable short circuits, matching units, crystal diodes and their mounts, bolometers and dry calorimeters, etc., have been made, and for transmission over moderate distances the vastly overmoded TE_{01} waveguide was used.

Introduction

TO AID a program of plasma diagnostics by the United Kingdom Atomic Energy Authority and, in particular, to facilitate the development of sensitive receivers[1] at 140 Gc and 280 Gc, a variety of components have been developed in waveguides RG136 and RG139, but no attempt has been made to make a complete range of components or to broadband them.

Fabrication techniques[2] include the use of the drawn waveguide, copper-gold eutectic bonding, precision milling, and especially, of electroforming. In several cases spark erosion techniques are used.

Dimensional tolerances are small—on the stainless steel mandrels usually used in the electroforming they are normally 0.1 or 0.2 mil, with surface finishes of 5 microinches or better.

Waveguide wall losses are high, measured attenuations being 2.73 db/ft at 140 Gc in RG136 guide and $6\frac{3}{4}$ db/ft at 280 Gc in RG139, both waveguides being drawn down from extruded coin silver RG99 waveguide. The comparable theoretical attenuations are 1.56 and 4.22 db/ft, respectively.

Despite these heavy attenuations and the small dimensions involved, quite useable components on conventional lines can be made in these waveguides, as the following examples will show.

* Received January 21, 1963; revised manuscript received April 29, 1963.

† Royal Radar Establishment, Great Malvern, Worcs., England.

[1] R. Meredith and F. L. Warner, "Superheterodyne Radiometers for Use at 70 Gc and 140 Gc," presented at the IRE Millimeter and Submillimeter Conference, Orlando, Fla.; January, 1963.

[2] A. F. Harvey, "Mechanical design and manufacture of microwave structures," IRE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, vol. MIT-7, pp. 402–422; October, 1959.

Ferrite Devices

A number of ferrite devices have been made, all based upon Faraday rotation methods, for which Ferramic R1 seems as suitable a material as any.

Designs are conventional, using 2-mil thick metalized mica vanes as filters, supporting the ferrite rod in a fine grain polyfoam cylinder and adjusting the rod length so that the ferrite is nearly saturated when giving rotations of ± 45 degrees. The only major problem encountered was the grinding of the rods, the sizes being only 16 mils diameter and about 9 mm long at 140 Gc and approximately 9 mils diameter at 280 Gc.

A typical isolator in RG136, but with the ferrite rod in 0.076-in diameter waveguide, has an insertion loss of $1\frac{1}{4}$ to $1\frac{1}{2}$ db. The isolation peaks at about 30 db, with a bandwidth at the 20-db level of about 2 Gc. By adjusting the axial magnetic field the peak isolation, which remains above 25 db, can be adjusted over the whole measurement range of 133 to 145 Gc.

Such devices are useable as amplitude modulators and, with a two port output, as switches; but if a reasonably fast modulating or switching rate is required, the metal waveguide wall must either be removed in the vicinity of the magnetic field or only an extremely thin wall used. Copper waveguide walls 0.1 mil thick can be made by plating a mandrel to this thickness, masking the required thin wall section and then building up the wall thickness on each side. The mask is then removed and the recess above the thin wall filled with epoxy resin before withdrawing the mandrel or dissolving it away. Using such a thin wall, switches have been made with a change-over time of about 3 μsec.

Slotted Line Standing Wave Indicators

Much thought was given to the various ways of measuring standing wave ratios, and it was concluded that, if moderate accuracy was required at these frequencies, high mechanical tolerances could not be avoided, and that the old fashioned probe and slotted line method was probably as rewarding as any.

A previous RG99 design was therefore scaled to RG136 and RG139 (Fig. 1). The construction is quite conventional; the main body, of brass, is split down the centers of the broad walls of the main guide. The two halves of the guide are milled and burnished, then a small part of the bottom walls removed so that, after the parts have been gold plated and assembled, a slot 10 mils wide and 15 mils deep is left.

The probe was originally turned to 3 mils diameter, but more recently a Wollaston wire has been used, which, after soldering to the top of an adjustable depth pin, is etched to leave a one-mil platinum wire as the probe. This has improved the performance considerably, and would now allow the slot width to be decreased. The probe couples out into an inserted electroformed cross guide, and so into a separate diode detector mount. The probe depth is adjustable, while in the cross guide a movable noncontacting piston can be set for best power transfer conditions from the main guide. The probe carriage moves on two precision ground steel bars which fit into jigbored holes in the main body. A friction drive is used, normally allowing five half-wavelengths movement, the position of the carriage being indicated by a clock micrometer reading in hundredths of a millimeter.

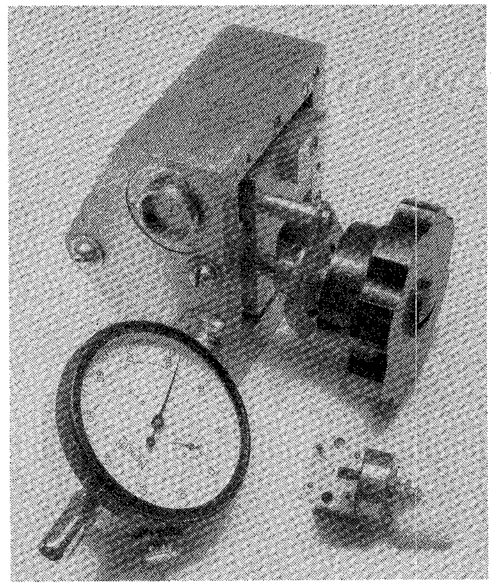

Fig. 1—1-mm standing wave indicator and detector.

The performance of a typical RG136 instrument shows an inherent mismatch of 1.05 when abstracting about 1 per cent of the power in the main guide. This mismatch is not due to the waveguide flange and is almost certainly caused by too wide a coupling slot. Repeatability of readings over the probe traverse is quite good, typical readings of the four possible VSWRs by taking adjacent maxima and minima of the probe outputs being 1.44, 1.44, 1.46 and 1.46. The waveguide loss in the guide over the $2\frac{1}{2}$ wavelengths travel is only such as to expect the previous VSWRs to increase by 0.02 on reaching the end nearest the test specimen. The insertion loss of the instrument is $\frac{3}{4}$ db, but the design places the probe as near the test specimen end as possible, so that the loss between the probe and the test specimen flange varies from about 0.21 db to about 0.33 db, depending on the position of the probe. For precision measurements this loss has to be considered.

A Matched Hybrid Tee

This component (Fig. 2) was electroformed on a disposable mandrel. In the RG136 versions the mandrels are of polystyrene, injection moulded in a collapsible metal mould, in the RG139 version a fusible alloy, "Cerrocast," is being tried since it flows better in the smaller waveguide size. In the first batch of components

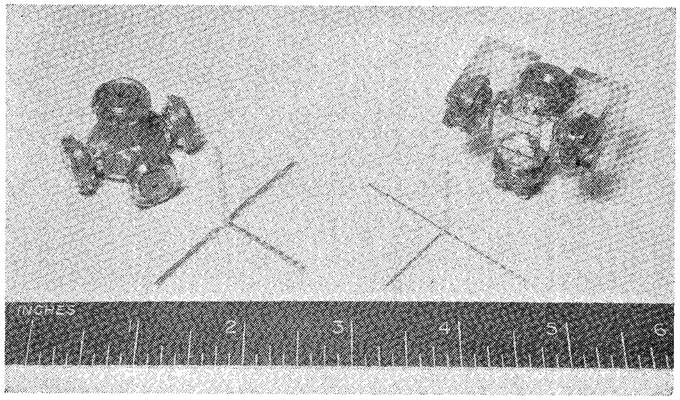

Fig. 2—2-mm magic Tee and its disposable mandrel.

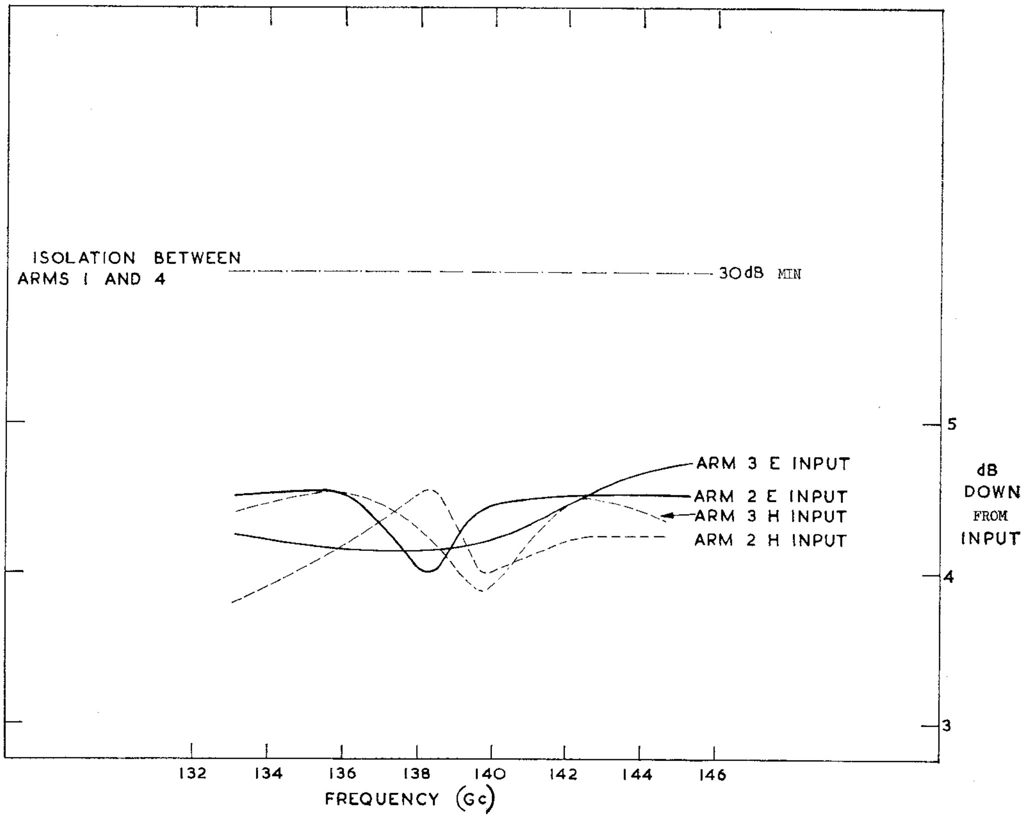

Fig. 3—Performance of 2-mm Tee.

a hole for the matching post and a slot for the matching iris were formed in the moulding operation, but it has been found more convenient to add these later. The post is 12 mils diameter and 25 mils high, the iris is a piece of foil 2 mils thick projecting 9 mils into the guide. After these two parts are inserted in the mandrel the whole is chemically silvered by a spraying technique and then electroformed in an acid copper bath.

Fig. 3 shows the performance of a typical Tee. Over the measured frequency range of 133 to 145 Gc the input power is split equally to $\pm\frac{1}{4}$ db, with a loss through the system of $1\frac{1}{4}$ db. The discrimination is greater than 30 db over the above frequency range, with an input match looking into any arm of not worse than 1.4 and usually about 1.25 near the designed frequency.

The tolerances obtained by this moulding process vary over a range of about one mil, which is much larger than the tolerances demanded from metal mandrels, yet the electrical performance is surprisingly reproduceable from Tee to Tee, presumably because symmetry is always maintained regardless of the absolute dimensions.

A Plug-in Crossed Guide Harmonic Generator

During the development of a 140-Gc second harmonic mixing superheterodyne receiver it was necessary to try a range of semiconductor materials, each prepared in different ways. To speed the measurements plug-in crossed guide diode mounts were developed (Fig. 4) using a copper-gold eutectic bonding process.

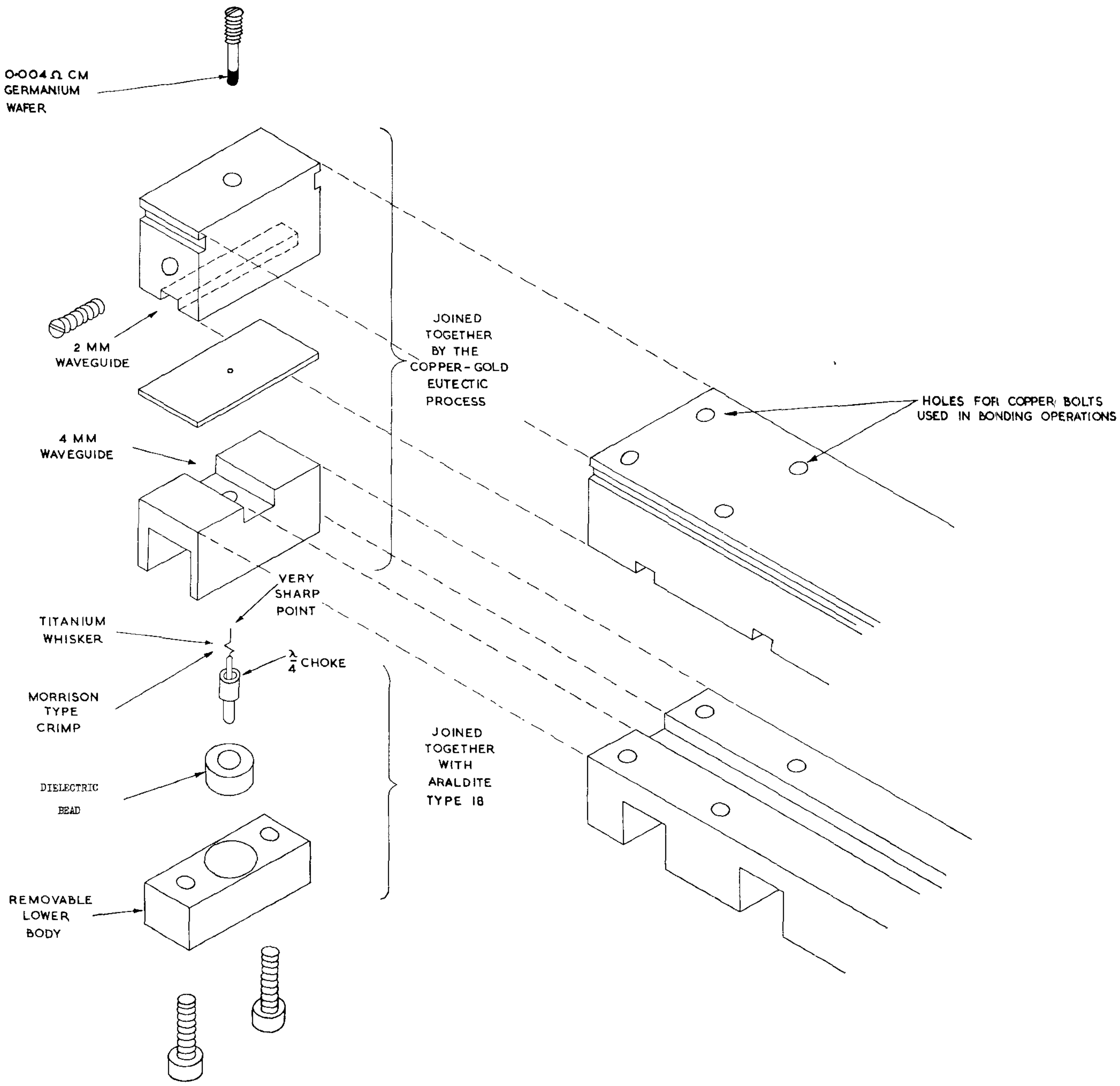

Fig. 4—Construction of the harmonic generator. Plug-in crossed guide H/G from RG99 to RG136.

The top part of the mount was part of a rectangular block of oxygen-free copper, several inches long, which had grooves 0.065 in wide by 0.0325 in deep milled and broached across it at intervals—these grooves later become the RG136 waveguides. The bottom section, of equal length and similar material, has an RG99 groove milled and broached along its whole length. A strip of copper foil 10 mils thick was placed between the other parts after each had been lightly gold plated, and all three components were clamped together with copper screws. The whole assembly was placed in an inert atmosphere and baked at 900°C for two hours. Under these conditions the copper and gold diffuse into each other to form an eutectic alloy and give a clean mechanical bond.

After this treatment a hole was jigbored through the block at each intersection of an RG99 and RG136 waveguide. These holes are opened out in the top and bottom pieces to hold the semiconductor and whisker parts and the assembly then sliced into individual plug-in items.

This copper-gold eutectic bonding enables waveguides to be cut in places which would result in intolerable losses if other techniques were used, and can afford considerable simplification in manufacture. For instance, an unmatched Tee or E-H Tuner may conveniently be made by milling the main guide along one edge of a cube and milling the E and H arms in the adjacent faces; only two flats are then required to complete the basic component.

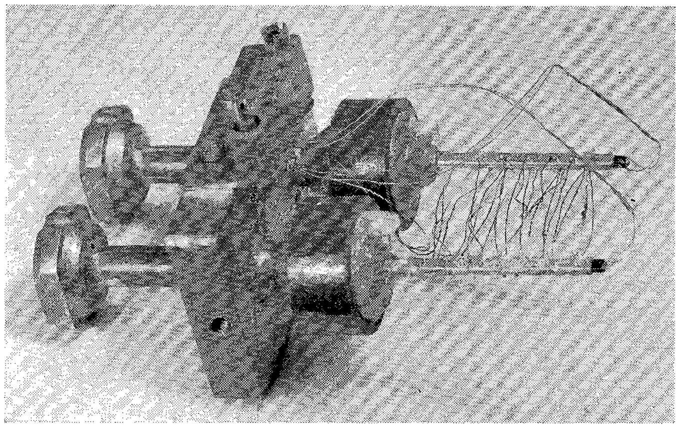

Fig. 5—2-mm dry calorimeter.

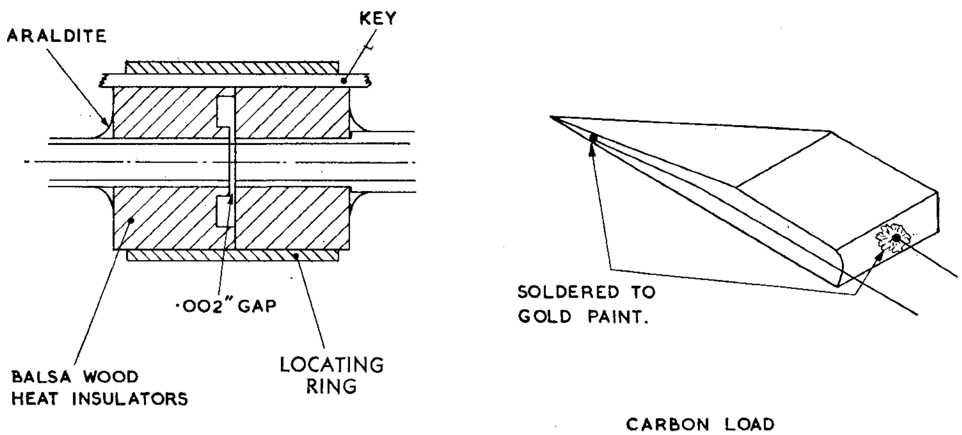

Fig. 6—2-mm calorimeter details.

Power Measuring Equipment

Accurate power measurement is essential if many other test bench measurements are to be meaningful or if useful comparisons are to be made with work in other laboratories. At an early stage a sophisticated RG99 dry calorimeter[3] was built, but while this was under development a very simple version was made which proved just as sensitive and quite as accurate. So when it came to making an RG136 calorimeter the simpler design was chosen.

This 2-mm calorimeter (Fig. 5) has two carbon loads, each of which can act as dc resistors as well as millimeter wave absorbers. These loads are wrapped in $\frac{1}{4}$-mil mica sheet to dc insulate them from the waveguide, which is made of 5 mils thick silver tube drawn over a mandrel. Heat insulation of this part of the guides is provided by fine grain balsa wood blocks which are parted off and turned back to leave a 2-mil gap in the waveguides (Fig. 6). The input sections of the two guides are plated to a reasonable diameter and strapped together by a copper plate. Twenty thin thermocouples measure the temperature differential of the two heat insulated sections.

[3] W. M. Sharpless, "A calorimeter for power measurement at millimeter wavelengths," IRE Transactions on Microwave Theory and Techniques, vol. MTT-2, pp. 45–47; September, 1954.

It is assumed, of course, that the same temperature rise is caused by the same input power, whether dc or millimeter wave. Power measurements agree to between 1 and 2 per cent, which ever guide absorbs the millimeter wave power, providing it is 1 mw or over. In its present form 100 μw can be read to 10 per cent accuracy, and the thermocouple output voltage is linear with input power up to about 30 mw, when convection becomes important—the instrument is not evacuated—but higher powers are still measurable, of course, by finding the dc power needed to null the thermocouple output. The time constant is 17 seconds, but this can be reduced at the expense of sensitivity.

It is intended to use this instrument at 1-mm wavelengths with a suitable taper, since it has been found that feeding 140 Gc power into the RG99 calorimeter in this way, sensible power measurements can be made.

Measurements of low millimeter wave powers are made using a 20-microinch diameter Wollaston wire bolometer (Fig. 7), mounted unevacuated as a single wire in a similar mount to that of the plug-in crystal detector and using the same detector holders. The video sensitivity of these bolometers, which have a response time of 100 μsec, is comparable to that of an unbiased silicon or germanium crystal diode.

In order to exploit this video sensitivity the milli-

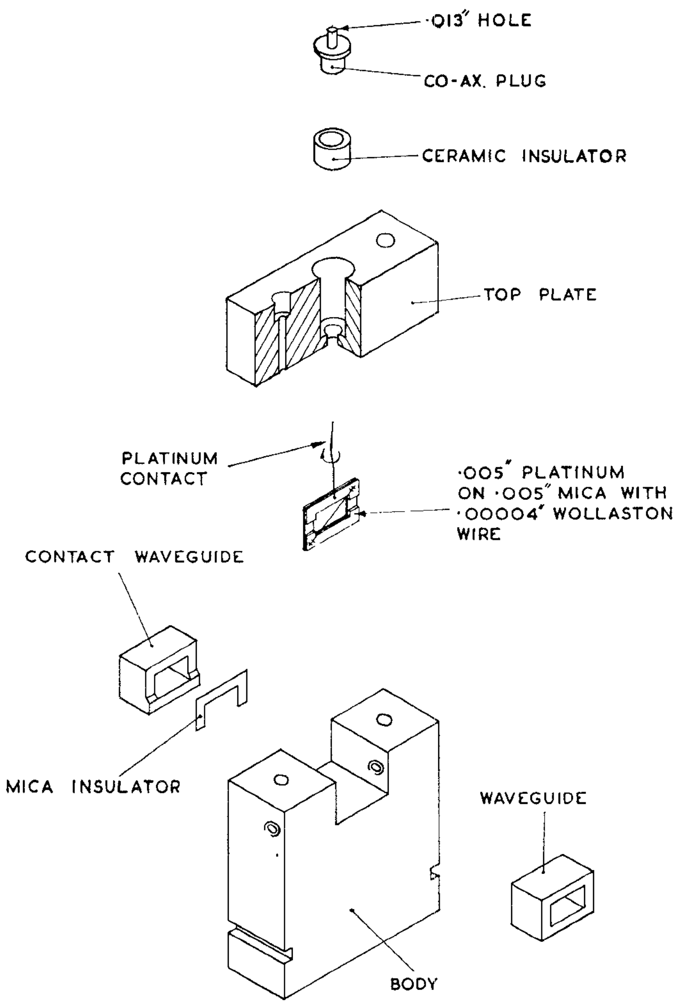

Fig. 7—2-mm bolometer construction.

meter wave power is measured by a technique involving square-wave modulating the power in the waveguide at 550 cps and injecting in the "50 per cent off" period a 1-Mc signal of variable but known voltage.[4] This voltage is adjusted until the output of a phase sensitive detector, locked to the chopper frequency, indicates equality of the unknown millimeter wave power and of the 1-Mc power. The voltage of the 1-Mc signal plus the known resistance of the bolometer at the bias current used enables the 1-Mc power to be calculated. This is assumed equal to the incident millimeter wave power.

However, when calibrated against the dry calorimeter the bolometer underreads by a factor of $2\frac{1}{4}$ to $2\frac{1}{2}$, even allowing for any millimeter wave mismatch. The source of such a large error is not known—loss in the millimeter wave chokes is very small, and the finite skin depth correction seems insufficient. Fortunately, as measured against power set initially by the dry calorimeter and varied by a rotary attenuator, this correction factor is virtually constant down to 0.1 μw, which appears to be the present limit of measurement with this equipment.

[4] Q. V. Davis, "A new precision low-level bolometer bridge," Proc. IRE (*Correspondence*), vol. 50, p. 2514; December, 1962.

Overmoded Rectangular Waveguide

A need for low loss transmission over moderate distances of, say, 30 feet is met by using simple oversized TE_{01} waveguide—in fact, standard 0.4 in × 0.9 in X-band guide. The launching tapers are simple linear ones, designed to ensure that the phase front at the exit from the taper is flat to $\lambda/8$ or less, the taper lengths being 8 in from RG136 and 19 in from RG139. The X-band guide is not specially treated except to ensure that the flanges are truely at right angles to the guide.

Due to a drawing error the tapers from RG136 launch the energy with the E-vector parallel to the narrow side of the X-band guide, which results in a theoretical attenuation at 140 Gc of 0.07 db/ft compared to a theoretical 0.03 db/ft if the electric field vector were parallel to the broad side. Experimentally the launching tapers have an insertion loss of 0.45 db and the straight overmoded waveguide an attenuation of 0.09 db/ft. The mode purity in the large guide is good, for, if two tapers are separated by ten feet of oversized guide and the transmitting frequency varied by 0.1 per cent the decrease in the power transmission of the system as various unwanted modes become resonant is not noticeable, and certainly less than 2 per cent.

In certain transmission experiments right-angled bends were needed. These were made in the X-band guide, with unmatched corners acting somewhat like optical flats. The loss introduced by such a corner was 0.8 db. Unfortunately no measurements have been undertaken to find out just which modes were excited by such a discontinuity, but no unusual effects have been noticed when using such corners with comparatively narrow-band receivers and transmitters.

Preliminary experiments with the same type of system at 280 Gc, but with the E-vector parallel to the broad face of the X-band guide, indicate an insertion loss of about 2 db for the taper from RG139 and a loss of less than 0.1 db/ft in the straight overmoded waveguide compared to the theoretical loss of 0.04 db/ft.

These long tapers are a straightforward electroplating job, using highly polished lucite mandrels which are silver plated by a spraying technique before being copper plated. The extraction of the mandrels is very easy—the mandrel and body assembly are hung apex upwards in a refrigerator; on cooling the lucite contracts more than the copper and the mandrel drops out.

Miscellaneous Components

An RG136 rotary attenuator uses 2-mil-thick metalized mica vanes, the central moveable vane having a maximum attenuation of appreciably greater than 40 db. The insertion loss is 1.4 db, and the theoretical law of the attenuator agrees extremely well with the variation in transmitted power through the attenuator as measured by the power measuring equipment over a 20-db range. In addition to the normal angular scale the vernier reading on the micrometer screw motion gives the attenuation directly over the range 5 to 25 db with an accuracy of ±0.1 db, which is often useful for rapid measurements. Over this same range the phase change through the instrument is 2 degrees.

For less accurate measurements flap attenuators are used, in which a differential screw motion moves a 2-mil thick metalized mica vane vertically through a 5-mil slot in the waveguide, the top of the slot being surrounded by loaded epoxy resin to eliminate leakage of power from the guide. The RG136 components have an insertion loss of 0.5 db, a range of 20 db and a resetting accuracy of about 0.03 db.

Variable short circuits are of the noncontacting type, with a cylindrical, choked piston moving in precision electroformed waveguide. The movement is through a micrometer screw, calibrated at 0.01-mm intervals. At 140 Gc VSWR's of 25 to 30 are obtained, corresponding to voltage reflection coefficients of 0.92 to 0.94.

For matching purposes a version of the pivoting screw tuner[5] is used, giving a very smooth action. The RG136 device uses an 8-mil diameter probe in a 12-mil wide slot and the RG139 version a 4-mil probe in an 8-mil slot. The slot and the recesses in the top waveguide wall, to allow the saddle holding the probe to pivot and still remain in close contact with the wall, are spark eroded in one operation using a tool as shown in Fig. 8.

[5] C. W. van Es, M. Gevers and F. C. de Ronde, "Waveguide equipment for 2 mm microwaves," *Philips Tech. Rev.*, vol. 22, No. 4, p. 113, No. 6, p. 181; 1960–1961.

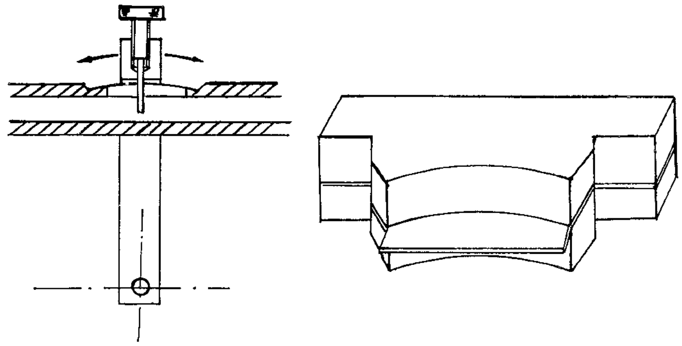

Fig. 8—Tool used in spark eroding a pivoting screw tuner.

Conclusions

Despite the small waveguide sizes and high wall losses it is possible to make useful waveguide components of a conventional type in fundamental mode rectangular guide for a wavelength of 2 mm and, almost certainly, of 1 mm.

Acknowledgment

This work would not have been possible but for the help of the Engineering Department, Royal Radar Establishment, and the aid of our colleagues of the Millimeter Wave Division.

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Submillimeter Components Using Oversize Quasi-Optical Waveguide*

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Summary—**Components such as directional couplers, attenuators, and phase shifters have been developed using optical techniques in oversize rectangular waveguide. These components were designed for operation in the 300- to 350-Gc range. They were scaled from a design that was successful at 27 Gc. Preliminary data taken at 330 Gc indicates the feasibility of this technique. The advantages of oversize waveguide as compared with conventional waveguide and free-space optical components are 1) lower attenuation and 2) simpler construction.**

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Introduction

THIS PAPER describes the development of components capable of operating at wavelengths below 1 mm. Generally, at frequencies above 300 Gc, components fabricated from conventional single-mode rectangular waveguide are not only excessively lossy (about 10 db per foot) but extremely difficult to construct. In an attempt to overcome this problem, several investigators designed millimeter components (interferometers and directional couplers) using free-space optical techniques. These devices were large structures that had the advantages of somewhat lower attenuation