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AN ADJUSTABLE SHORT-CIRCUIT FOR MILLIMETER WAVEGUIDES

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I. Introduction

Adjustable waveguide short-circuits are used as tuners in many millimeter wave applications, and are often lossy and unrepeatable. Commercial millimeter-wave components have even been made with waveguide short-circuits consisting simply of loose-fitting metal strips held in place by a set-screw. Figure 1 shows the measured return loss of such a short at K_u-band; it is unacceptably lossy over the whole waveguide band (between the markers).

This report describes a non-contacting short-circuit for use in full-height WR-4 waveguide (170-260 GHz). Its loss is low, and the phase of its reflection coefficient varies smoothly across the full waveguide band. The design can be scaled for use in any millimeter waveguide band.

A. Requirements for a Good Adjustable Waveguide Short-Circuit

The essential requirements for an adjustable waveguide short-circuit are: (i) low loss, (ii) smooth variation of the phase of the reflection coefficient with frequency, (iii) smooth variation of phase as the short-circuit is moved, and (iv) good repeatability.

B. Contacting Versus Non-Contacting Shorts

In the standard millimeter waveguide bands, non-contacting short-circuits are commercially available. These usually consist of a metal dumbbell, often teflon coated, which rotates on the end of a long micrometer shaft. Centering of the dumbbell in the waveguide is not easy to ensure. It has been common experience that such shorts can be lossy in some part of their frequency range. From the measurements described here, the most likely cause of this loss appears to be off-center mounting of the dumbbell.

In the microwave bands, adjustable shorts are commercially available which use plungers with rectangular or circular cross-sections. As will be shown below, rectangular non-contacting plungers are prone to in-band resonances if they are not precisely centered in the waveguide, which makes them unsuitable for millimeter wavelengths.

In reduced height millimeter waveguide, non-contacting dumbbell short-circuits are difficult to make because of the small dimensions and clearances involved. For example, a WR-10 (75-110 GHz) mixer may have its waveguide height reduced to 1/4 of full height -- i.e., to 0.0125". Non-contacting plungers of rectangular cross-section, centered in the waveguide by a layer of mylar adhesive tape [1], have achieved some success, but our experience indicates that carefully made contacting shorts are superior in reduced height waveguide.

Contacting short circuits have two main loss mechanisms: resistive loss at the contact points, and loss due to power leakage into the gap behind the contact points. This latter loss is caused by the contact fingers (or strips) acting as antennas to couple power from the incident wave into the slender waveguides formed between the body of the short-circuit and the upper and lower waveguide (broad) walls. This might be overcome by using multiple quarter-wave spaced contacts; however, contacting short-circuits cannot readily be made with multiple sections. Wear can limit the lifetime of contacting short-circuits. We have found this can be minimized by carefully rounding the tips of contact fingers and using heavy gold plating on the sliding short and on the inside of the waveguide [2].

This report will not deal further with contacting short-circuits nor with short-circuits in reduced-height waveguide.

C. The Quarter-Wave Plunger as a Waveguide Short-Circuit

Within their normal operating bands, rectangular waveguides propagate only the dominant TE_{10} mode. Introducing a conducting plunger into the waveguide creates a gap which supports the coaxial TE_{11}-like mode (like two rectangular TE_{10} modes wrapped around the plunger as shown in Figure 2(a)), and the same mode rotated 90° -- Figure 2(b). Also, the coaxial TEM mode is supported -- Figure 2(c). Depending on the plunger dimensions and the presence of any dielectric material in the gap around the plunger, higher-order gap modes may also be supported within the normal waveguide band.

If the rectangular plunger is perfectly centered in the waveguide, the incident rectangular TE_{10} mode excites the coaxial TE_{11} gap mode and also higher order (evanescent) gap modes with anti-symmetry about the virtual short-circuit plane in Figure 2(a). A non-contacting short-circuit can be made using a series of high and low characteristic impedance quarter-wave long rectangular plungers. The length of the sections is based on the guide wavelength of the coaxial TE_{11}-like gap mode (Figure 2(a)), and should be corrected for the fringing fields associated with the evanescent gap modes.

If the plunger is off center vertically, the incident mode will also excite the coaxial TEM mode and higher-order (evanescent) gap modes with both vertical and horizontal symmetry. If the plunger is diagonally off center, then the 90°-rotated coaxial TE_{11}-like gap mode (Figure 2(b)) will be excited together with the corresponding set of 90°-rotated higher-order modes.

The sharp resonances in many of the measurements below are attributed to resonances between pairs of undesired modes all of which are reactively terminated at the far end of the plunger. It appears to be generally true that plungers which are diagonally off center have more in-band resonances than those which are vertically or laterally off center. This is a result of coupling between the incident TE_{10} waveguide mode and two sets of gap modes, one rotated 90° relative to the other in the diagonally off-centered case.

The above discussion applies equally to rectangular and circular plungers in rectangular or circular waveguides.

It may be tempting to fill the gap around a waveguide plunger with a dielectric material to improve the performance of the short-circuit and to help center the plunger. However, there are some disadvantages to this approach: (i) The presence of the dielectric lowers the cut-off frequencies of the higher-order gap modes, which increases the likelihood of in-band resonances. (ii) In practice, some clearance is needed between the dielectric and the waveguide walls. Lateral movement of the plunger within this air gap may cause greater changes in loss or phase than would occur in the absence of dielectric. (iii) Fabrication of millimeter waveguide short-circuits with dielectric supports is a non-trivial additional complication. For these reasons, and because it is possible to make a good short-circuit without dielectric supports, we do not consider dielectric-filled short-circuits further here.

II. Measurements

In this and the following sections we describe measurements on a number of K_u-band waveguide plungers and dumbbells. These measurements were made on a HP 8510 microwave network analyzer over the frequency range 10-20 GHz. In all figures in this report showing measured results, two frequency markers are used to indicate the edges of K_u-band (12.4-18 GHz). Except where explicitly noted, plungers or dumbbells are arbitrarily located along the waveguide and are not necessarily positioned at the measurement reference plane.

A. Rectangular Plungers

Initially it seemed desirable to use a plunger which would block as much as possible of the waveguide cross-section. It soon became apparent, however, that a plunger considerably narrower than the waveguide was much less susceptible to in-band resonances. Figure 3 shows the magnitude and phase of S_{11} for a typical rectangular plunger in K_u-band waveguide (12.4-18.0 GHz). In Figure 3(a) the plunger is carefully centered between polystyrene foam supports ($\epsilon_r \approx 1.0$) and no undesired in-band resonances are evident. In Figure 3(b) the plunger is slightly off center and a sharp resonance is visible near 17.4 GHz. A slight rotation of the plunger (about the waveguide axis) excited a resonance near 13.6 GHz as shown in Figure 3(c). A rotated and off-center plunger exhibits both these resonances, as shown in Figure 3(d). The height of this plunger was chosen to give a 0.002" clearance to the waveguide broad walls when scaled to WR-4 waveguide (170-260 GHz).

To improve the 0.4 dB return loss of this plunger, an additional identical section was added at various distances from the first section.

Typical results are shown in Figure 4 for three spacings. A return loss < 0.05 dB is achievable across most of the band, but always with at least one resonance. (With perfect centering of the plungers, resonances could probably have been avoided.)

It seems clear from these and other experiments that it would be difficult to make an acceptable millimeter wave short-circuit using a rectangular plunger. Mechanical tolerances would not allow sufficiently precise location of the plunger to ensure resonance-free operation.

B. Circular Plungers

Our initial measurements on circular plungers were on a HP Model P920B K_u-band unit. This has a copper dumbbell which rotates on the end of a micrometer shaft as shown in Figure 5. Measurements of S_{11} for the HP short are shown in Figure 6(a). The return loss is < 0.02 dB (the measurement noise limit) across the band, and the phase variation is well behaved. The effective short-circuit plane is located 0.015" behind the end of the dumbbell (i.e., away from the source) as indicated in Figure 6(b). The effect of moving the short towards the waveguide broad wall is shown in Figures 7(a) and (b). It is clear that only relatively large movements away from the waveguide centerline cause a resonance to move into the waveguide band.

The HP design is in most respects suitable for scaling to millimeter wavelengths. However, the 0.006" clearance between the dumbbell and the waveguide wall is too small; in WR-4 waveguide (170-260 GHz) the corresponding clearance would be 0.0004" which is impractical. For this reason we tested a series of dumbbells (Figure 8) with progressively smaller diameters but having other dimensions the same as the HP design. These dumbbells were supported in a section of waveguide by polystyrene foam. Figure 9 shows S_{11} for the dumbbell with the original HP dimensions, and Figures 10(a)-(c) show S_{11} and $|S_{21}|$ for the smaller dumbbells.

From these measurements on simple three-section dumbbells, it was clear that additional sections would be needed if the dumbbell diameter were to be in a reasonable range for scaling to millimeter wavelengths. Five- and seven-section dumbbells of diameter 0.253" (Figure 11) were measured, with the results shown in Figure 12. The smaller return loss and slightly wider $|S_{11}|$-bandwidth of the seven-section dumbbell make it a good choice for millimeter wave application. The 0.253" diameter and 0.029" wall clearance of the K_u-band dumbbell correspond to 0.0175" diameter and 0.002" wall clearance when scaled to WR-4 waveguide (0.0430" x 0.0215").

III. The Millimeter Wave Design

The seven-section 0.253" diameter dumbbell was mounted in the end of an aluminum holder of cross-section 0.614" x 0.303", i.e., 0.008" smaller in each dimension than the waveguide. This clearance was chosen to simulate a 0.0005" clearance in WR-4 waveguide. The end section of the dumbbell was now entirely inside the holder. Figure 13 shows the measured S_{11}. In Figure 13(a) the end of the dumbbell is located at the measurement reference plane, while in Figure 13(b) the dumbbell is moved towards the source 0.090" to give the flattest phase variation across the band. From this, the short-circuit can be characterized as a constant reflection coefficient of unit magnitude and phase -130°, located 0.090" from the end of the dumbbell, or, equivalently, a constant normalized impedance of -j0.46 located at the same place.

Figure 14 shows that bending the dumbbell substantially towards the broad wall or narrow wall of the waveguide does not produce any in-band resonances. Bending the dumbbell substantially towards the corner of the waveguide, however, causes two very sharp in-band resonances as shown in Figure 15(a). These resonances can be suppressed, as shown in Figure 15(b), by putting lossy ferrite beads on the end of the holder. This is probably the reason for the use of absorbing material in the HP design (Figure 5). Even in the present measurements with a greatly off-center dumbbell, these resonances were weakly coupled to the TE_{10} waveguide mode and are barely discernable on the phase plot. At millimeter wavelengths, the greater conductor loss will tend to suppress these resonances (as did the absorbing beads). Certainly, a dumbbell reasonably centered by eye should have a resonance-free response.

IV. Design for WR-4 Waveguide (170-260 GHz)

A. Construction

Scaling the above design from K_u-band to WR-4, a factor of 14.5 in frequency (and linear dimensions), results in a dumbbell structure with diameters 0.0175" and 0.0086". To machine this on a lathe was judged impractical, so the short-circuit was assembled from simpler components -- brass beads on a copper-plated steel rod, mounted on the end of a brass carrier. To obtain the necessary precise alignment (± 0.0002"), an assembly jig holds all these components in place on a hot-plate while low temperature solder is applied. After assembly the whole structure is gold plated.

The WR-4 short-circuit assembly is shown in Figure 16. Figures 17 and 18 give details of the assembly fixtures.

B. Drive Mechanism

At short millimeter wavelengths it is desirable to control the position of a short-circuit to micron accuracy, and for this reason the drive mechanism, shown in Figure 19, has a #000-120 lead screw (0.0083"/turn). A rotating nut moves the non-rotating lead screw which is a part of the short-circuit assembly. The mechanism is compact enough to allow two to be mounted on the back of a WR-4 mixer block. Friction is very low, and the mechanism is suitable for cryogenic operation provided oil is removed from the ball races.

V. References

[1] M. K. Brewer and A. V. Räisänen, "Dual-Harmonic Millimeter Waveguide Backshorts: Theory, Design, and Test," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, no. 5, pp. 708-714, May 1982.

[2] V. Summers, "Chemical Lab Procedures, 1988," Chemical Lab Report No. 7, National Radio Astronomy Observatory, Charlottesville, VA 22903, Jan. 1988.

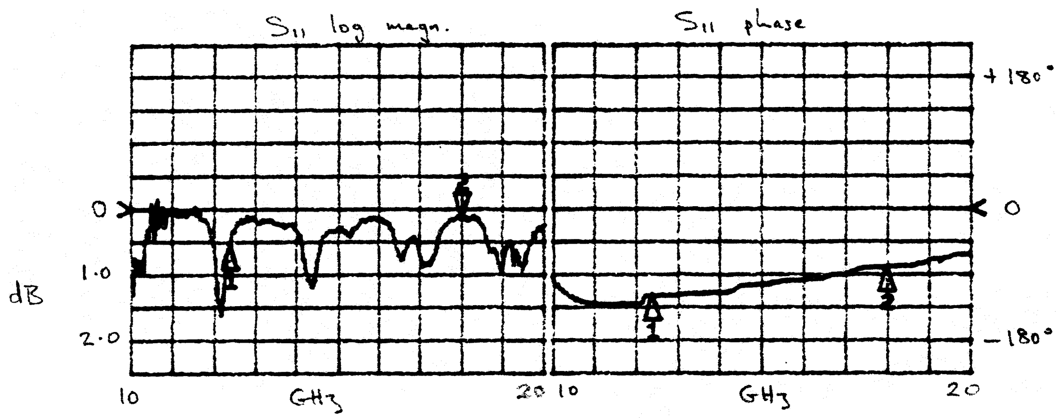


Fig. 1. S_{11} magnitude and phase for a rectangular bar inside a WR-62 waveguide (0.622" x 0.311"). The bar is 0.007" smaller than the waveguide in both dimensions.

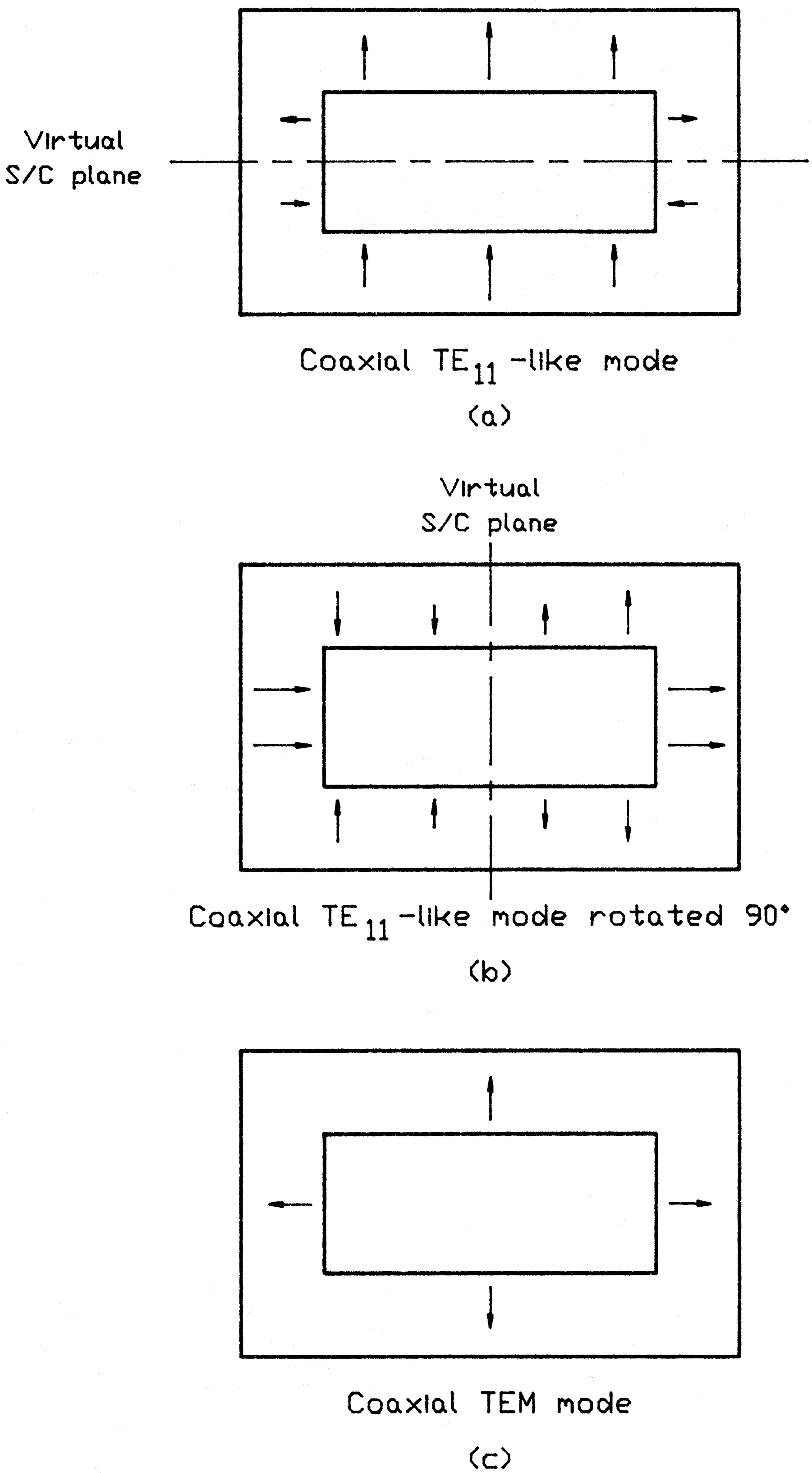


Fig. 2. E-field patterns of modes in the gap between a plunger and the waveguide. The coaxial TE_{11}-like gap mode (a) is excited by the incident rectangular waveguide TE_{10} mode. If the plunger is laterally off center, the 90°-rotated version of the same mode (b) is also excited. If the plunger is vertically off center, the coaxial TEM mode (c) is also excited.

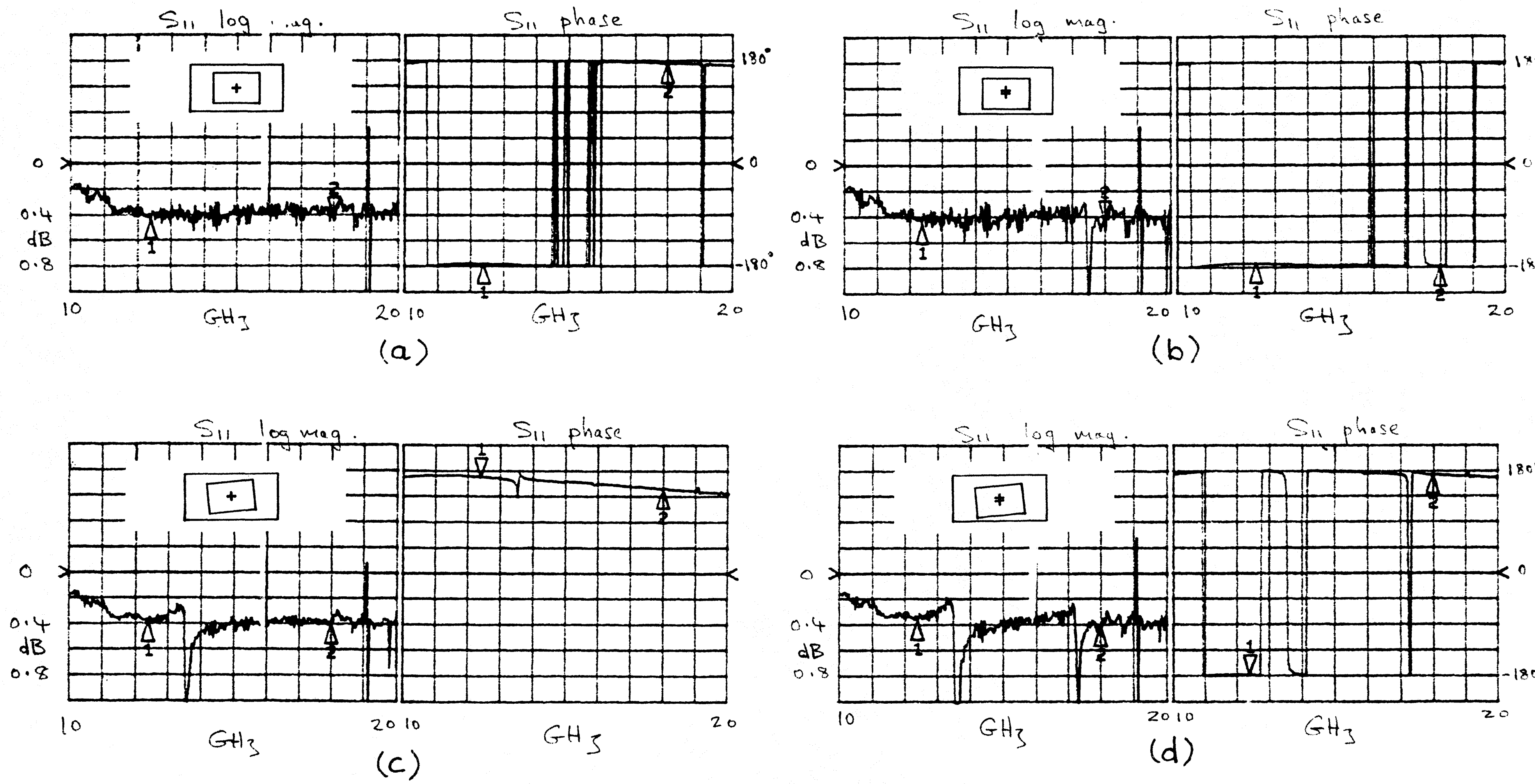


Fig. 3. S_{11} magnitude and phase for a single rectangular plunger 0.311" x 0.253" x 0.117" long in a terminated K_u-band waveguide (0.622" x 0.311"). In Fig. 3(a) the plunger is centered between polystyrene foam supports and no undesired in-band resonances are evident. In Fig. 3(b) the plunger is slightly off center and a sharp resonance is visible near 17.4 GHz. In Fig. 3(c) the plunger is slightly rotated (about the waveguide axis) and a resonance appears near 13.6 GHz. A rotated off-center plunger exhibits both resonances, as shown in Fig. 3(d).

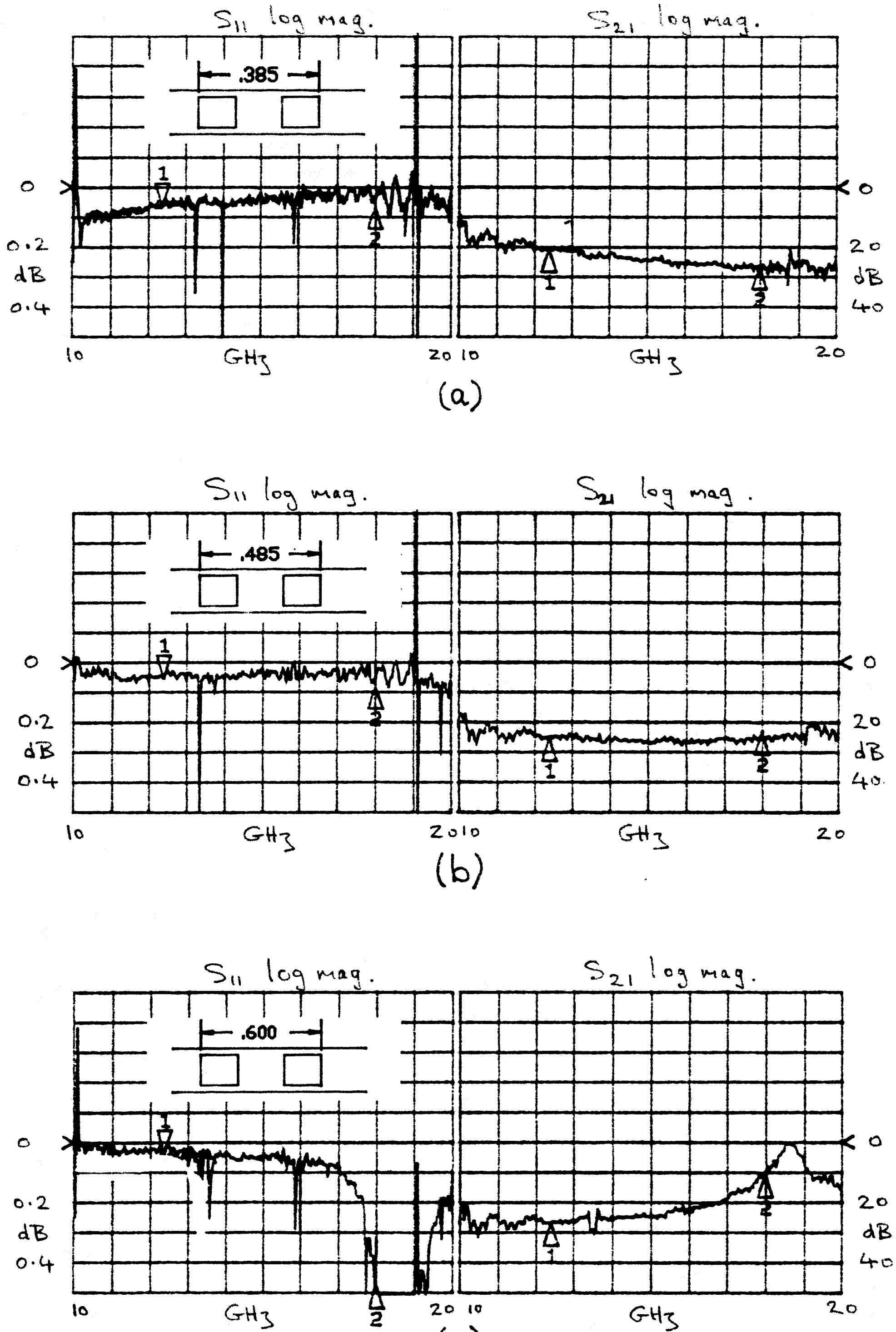


Fig. 4. Magnitudes of S_{11} and S_{21} for two plungers with various separations. Each plunger is identical to the one in Fig. 3. Overall lengths of the two-plunger assembly are: (a) 0.385", (b) 0.485", and (c) 0.600".

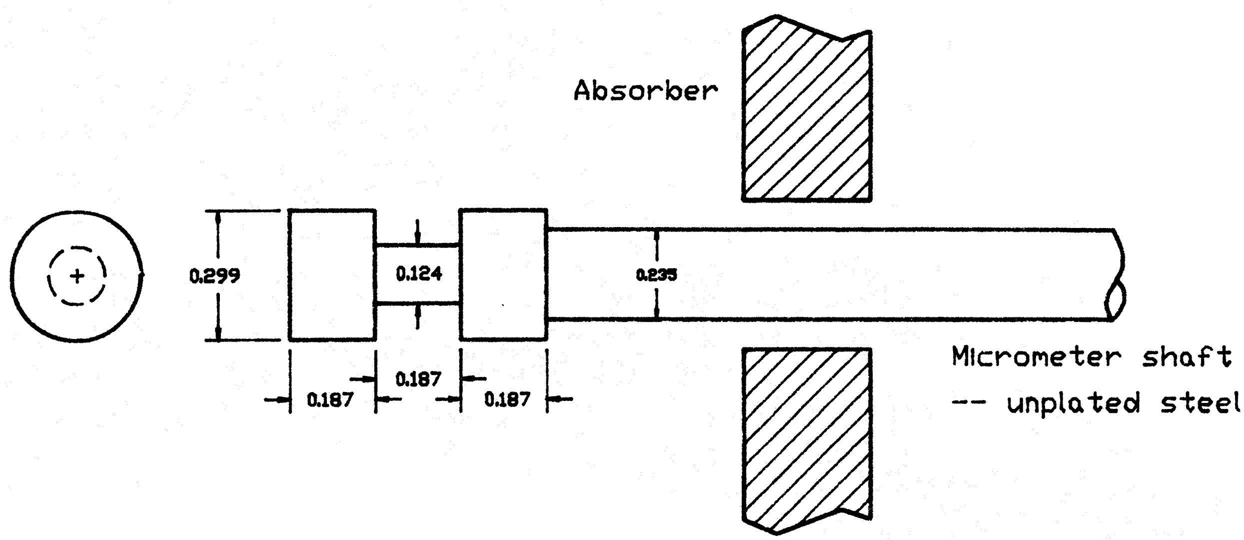
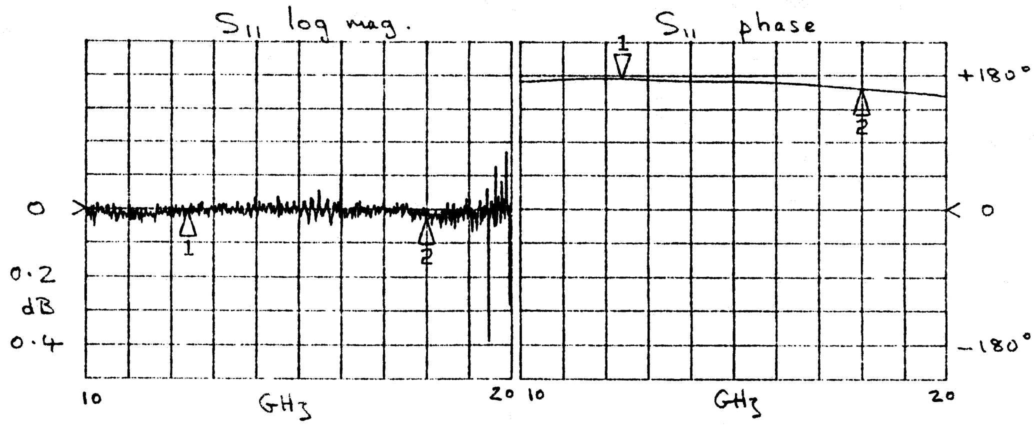
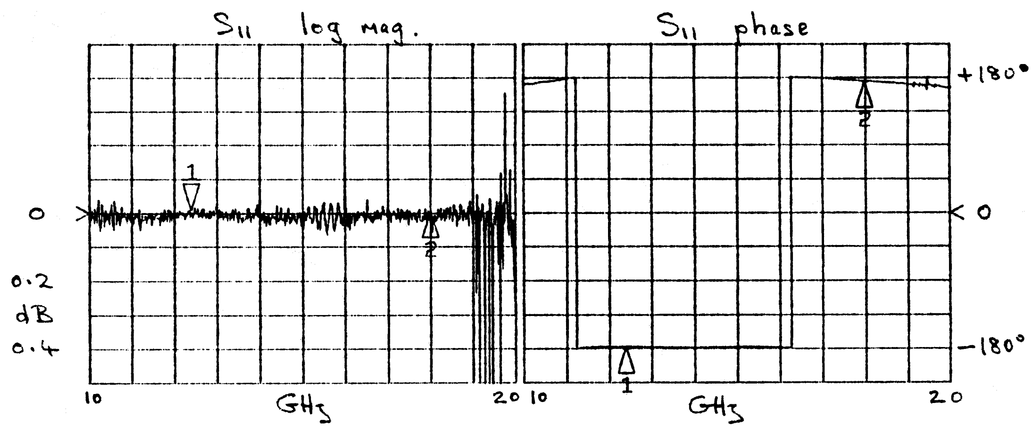


Fig. 5. Details of a HP Model P920B K_u-band sliding short. The copper dumbbell rotates on the end of the micrometer shaft. Absorbing material is placed behind the dumbbell. Clearance between the dumbbell and the waveguide broad walls is 0.006" above and below.

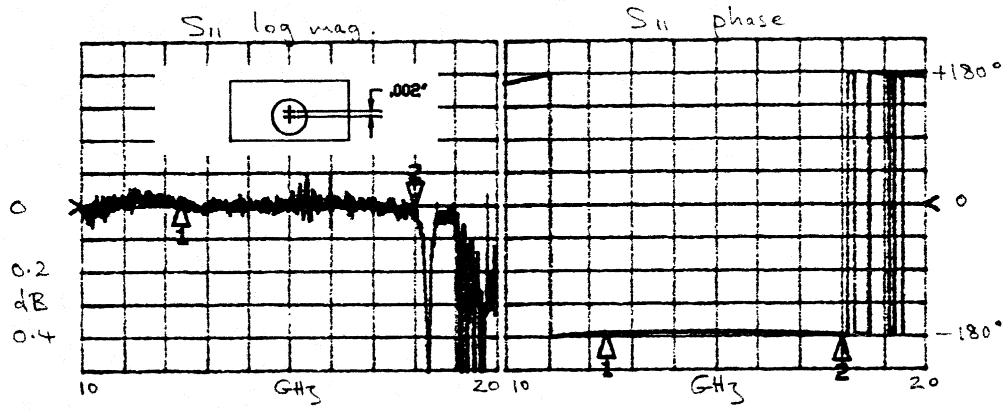


(a)

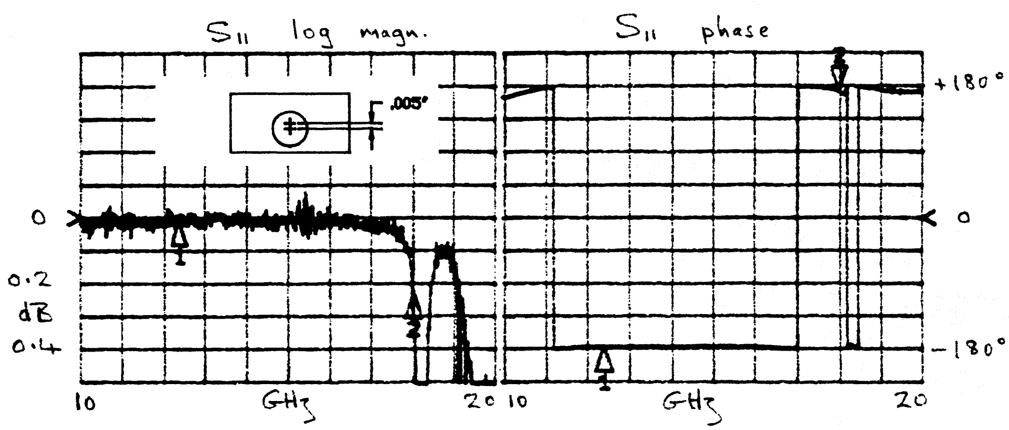


(b)

Fig. 6. (a) S_{11} for the HP short with the end of the dumbbell located at the measurement reference plane. The return loss is < 0.02 dB (the measurement noise limit) across the band, and the phase variation is well behaved. (b) S_{11} with the short positioned to give the flattest phase variation (by eye). This occurs when the end of the dumbbell is located 0.015" in front of the reference plane (i.e., towards the source).



(a)



(b)

Fig. 7. The effect of moving the short towards the waveguide broad wall. (a) The dumbbell is 0.002" off center (0.004" gap to the waveguide wall). (b) The dumbbell is 0.005" off center (0.001" gap).

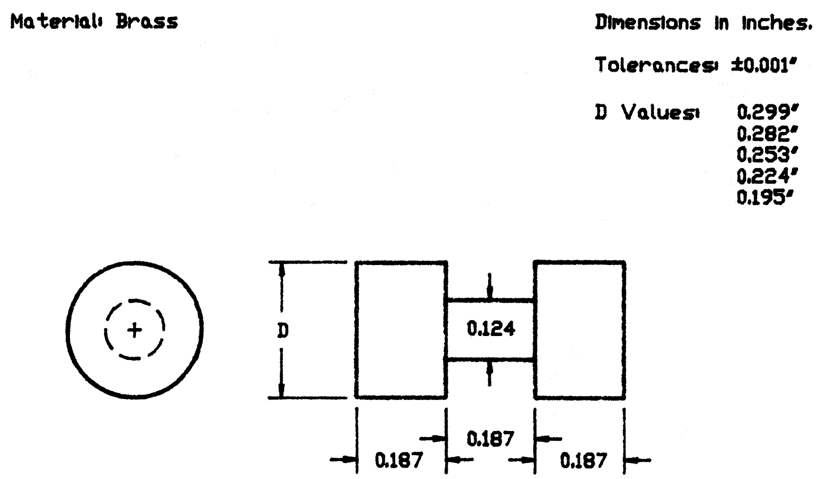


Fig. 8. Dumbbells with different diameters used for measurements in Figs. 9 and 10.

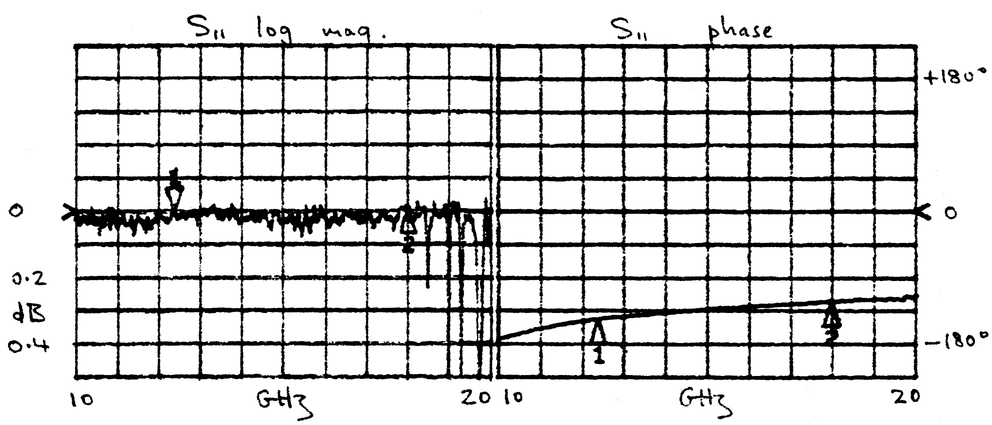


Fig. 9. S_{11} for the dumbbell with the original HP dimensions (0.299" dia.).

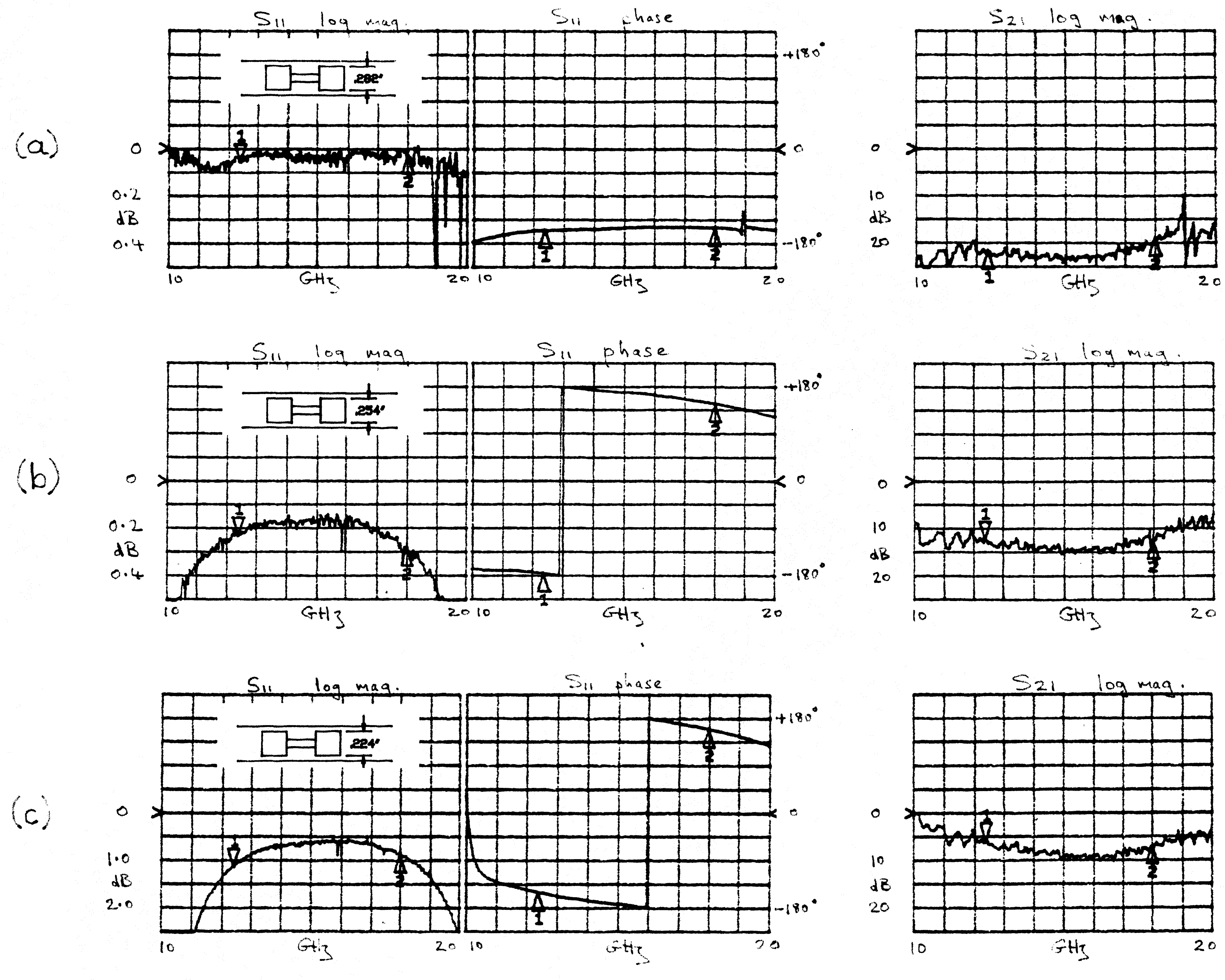


Fig. 10. S_{11} and $|S_{21}|$ for the dumbbells with diameters: (a) 0.282", (b) 0.254", and (c) 0.224".

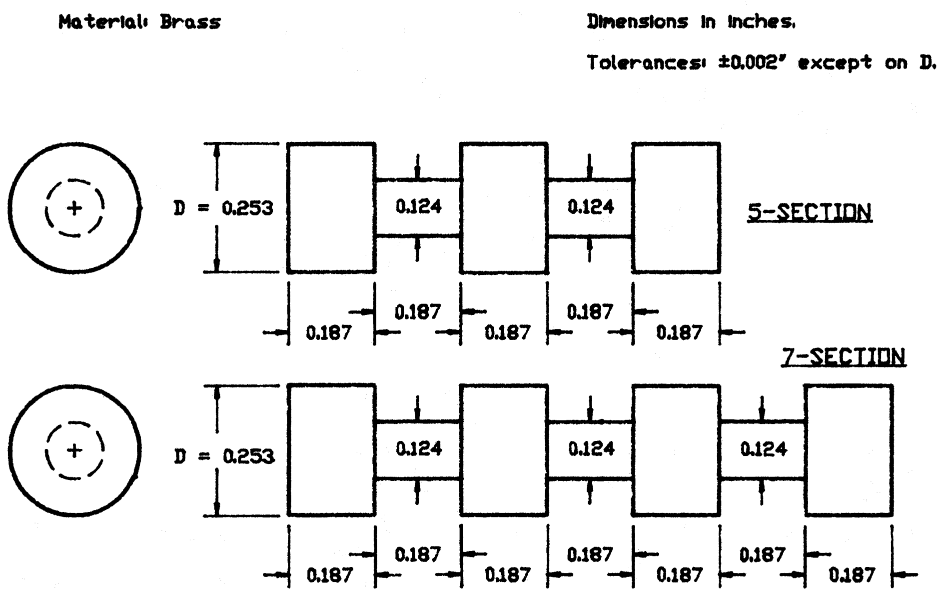


Fig. 11. Five- and seven-section dumbbells of diameter 0.253". The 0.253" diameter and 0.029" wall clearance of the K_u-band dumbbell correspond to 0.0175" diameter and 0.002" wall clearance when scaled to WR-4 waveguide (0.0430" x 0.0215").

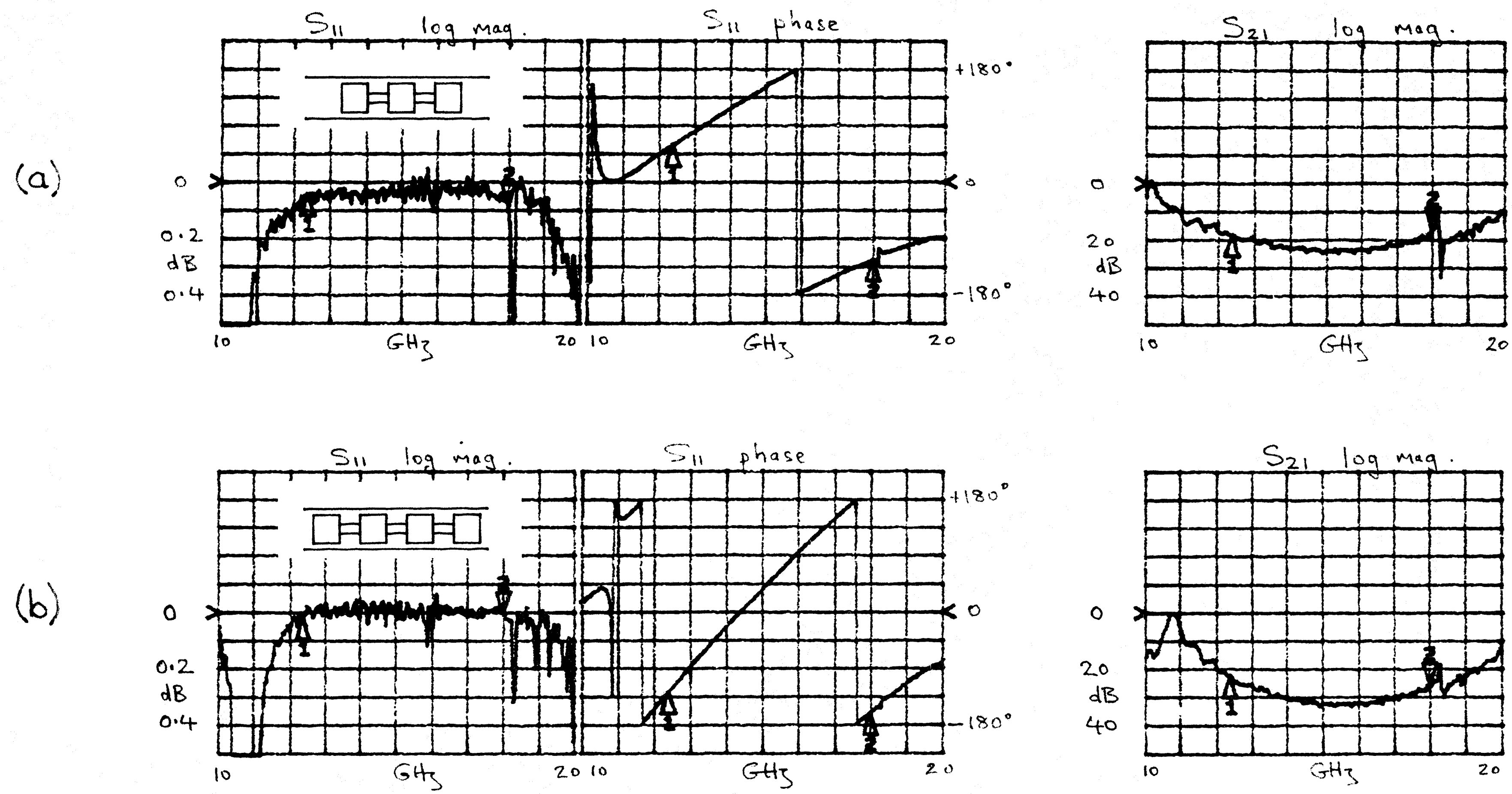
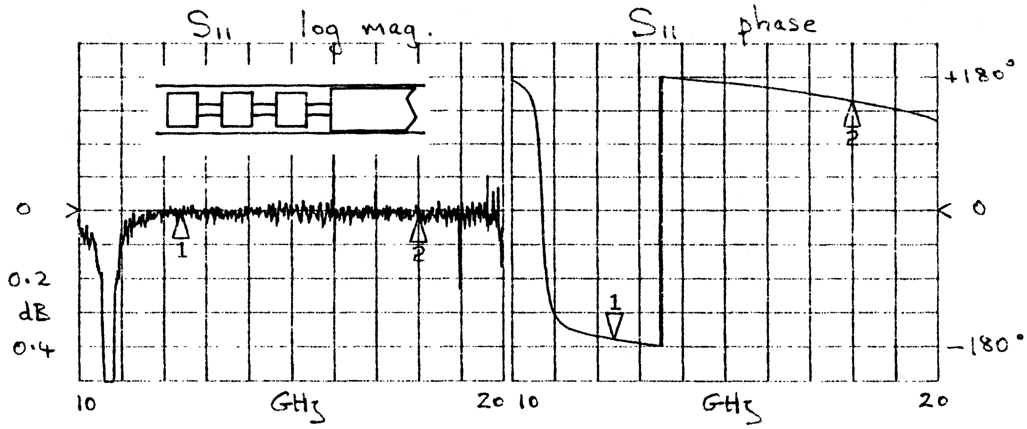
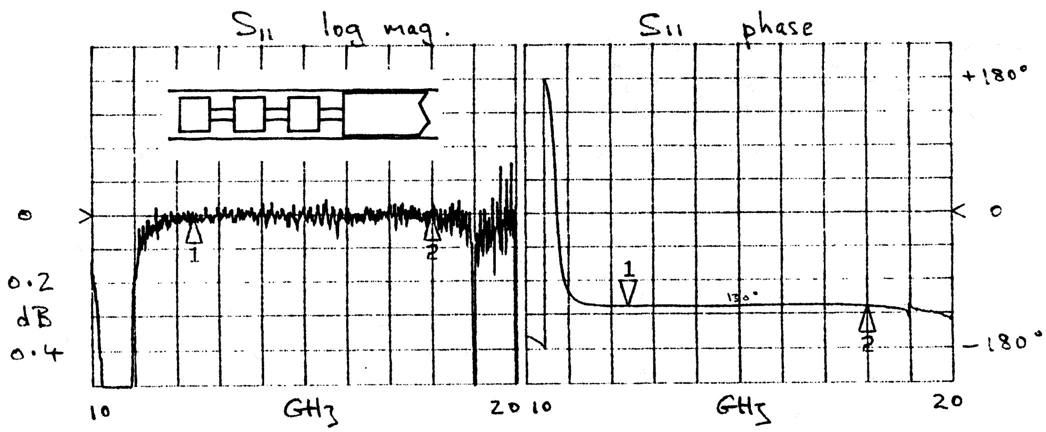


Fig. 12. S_{11} and $|S_{21}|$ for 0.253" diameter dumbbells with (a) five sections, and (b) seven sections. The smaller return loss and slightly wider S_{11}-bandwidth of the seven-section dumbbell make it a good choice for millimeter wave applications.



(a)



(b)

Fig. 13. S_{11} magnitude and phase for the 0.253" diameter seven-section dumbbell supported in a metal holder (see text). In (a) the end of the dumbbell is located at the measurement reference plane, while in (b) the dumbbell is moved towards the source 0.090" to give the flattest (by eye) phase variation across the band.

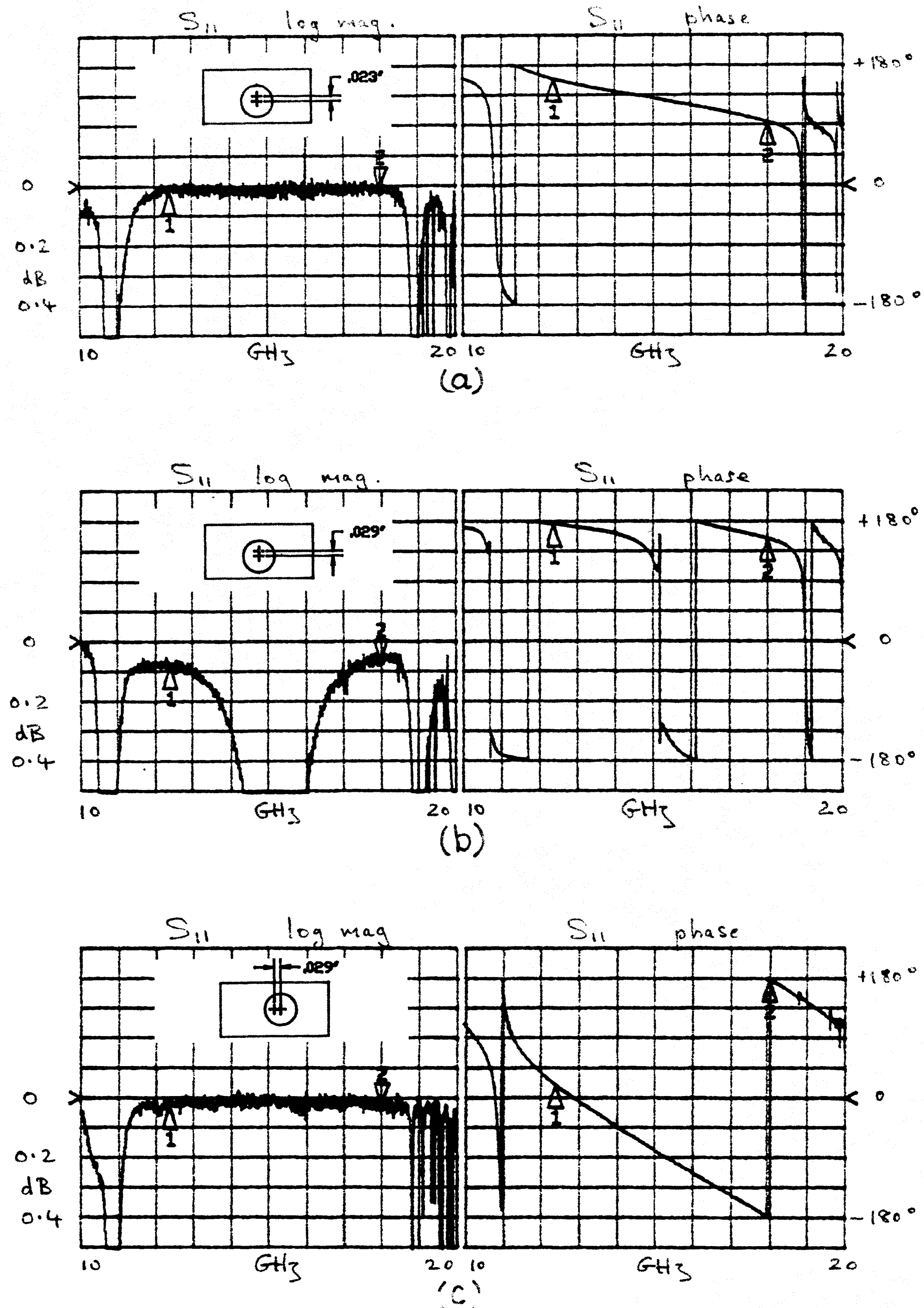


Fig. 14. The effect of bending the dumbbell in its holder so the end is: (a) 0.023" off center towards the waveguide broad-wall (0.006" gap), (b) 0.029" off center towards the waveguide broad-wall (i.e., just touching the wall), and (c) 0.029" off center towards the waveguide <u>narrow</u>-wall.

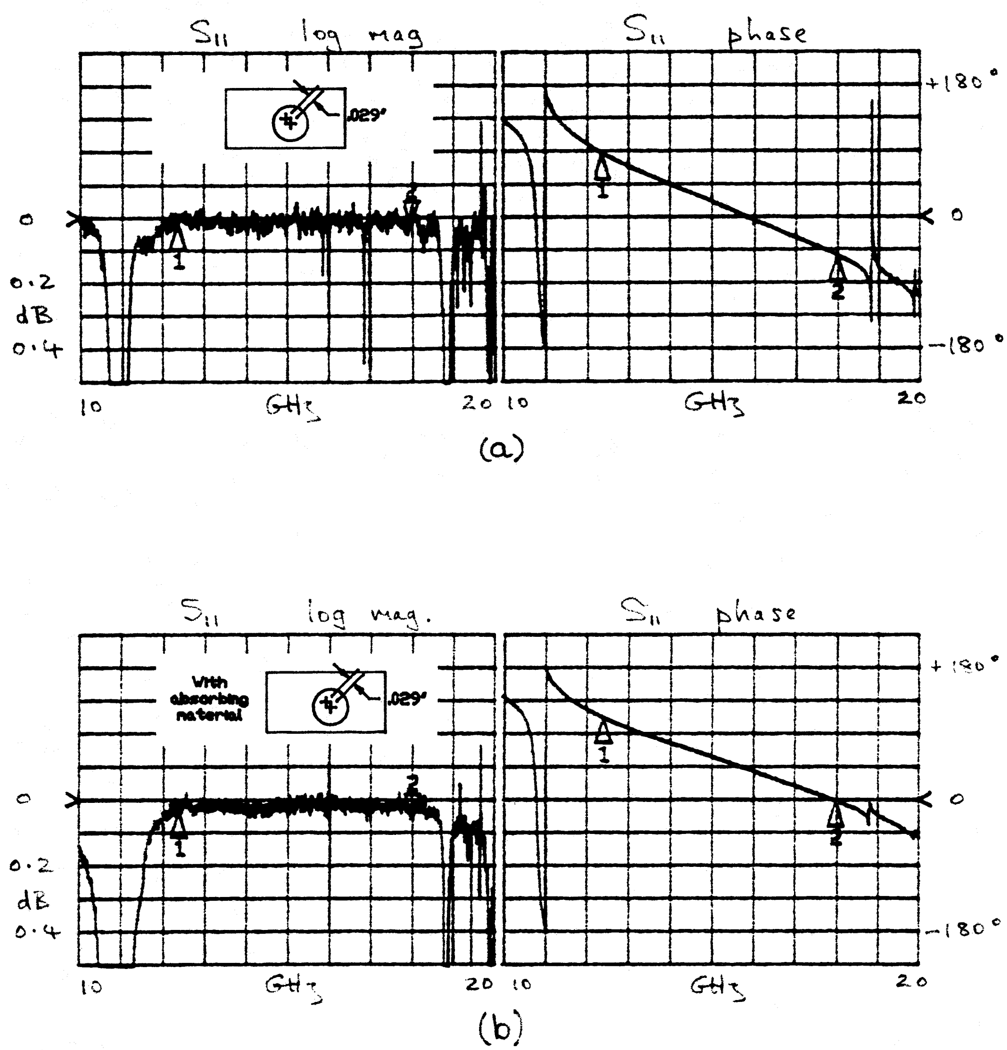
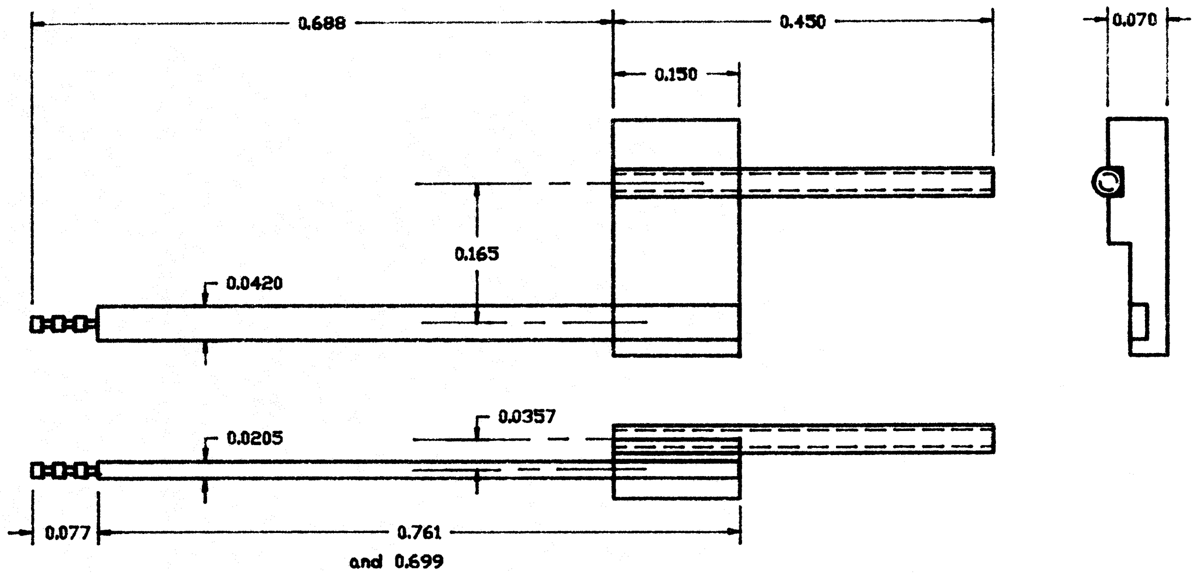
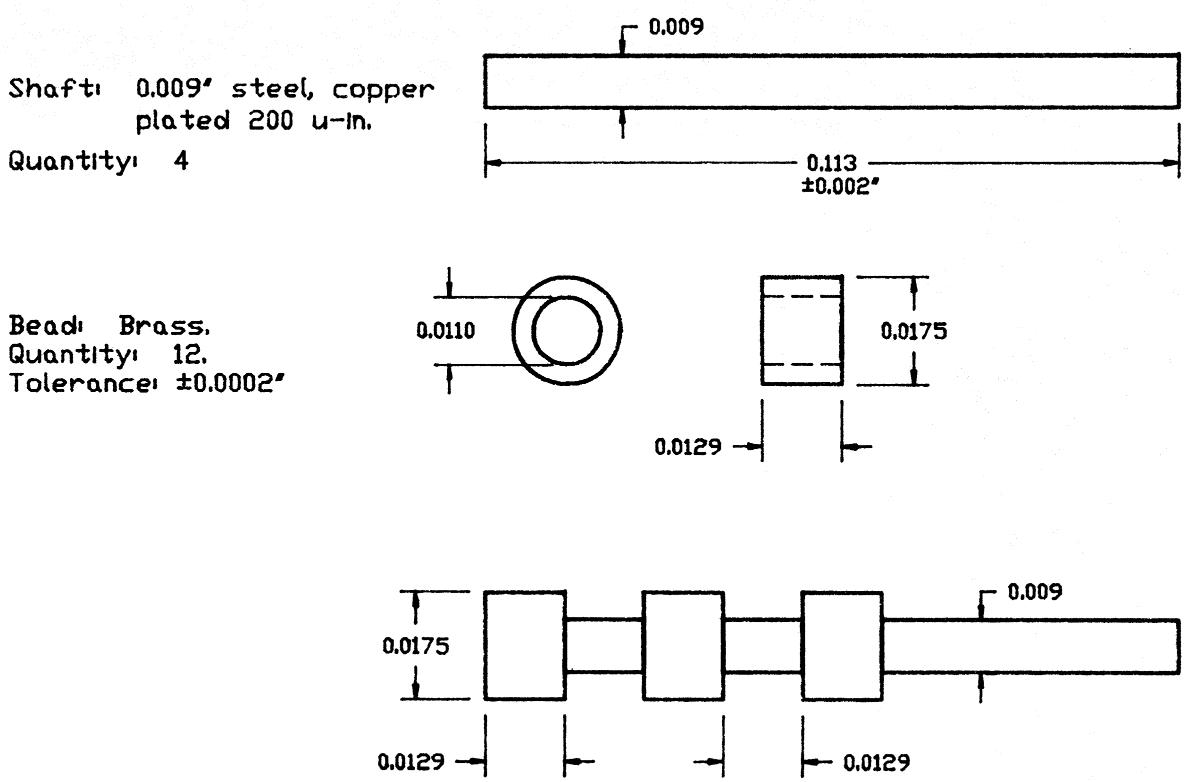


Fig. 15. (a) The effect of bending the dumbbell in its holder so the end is 0.029" off center at 45° to the waveguide axes. (b) The same, but with absorbing beads attached to the end of the holder.



(a)



(b)

Fig. 16. (a) The WR-4 short-circuit assembly including the rectangular holder, which centers the dumbbell in the waveguide, and the #000-120 lead-screw. (b) The copper plated steel shaft and brass beads.

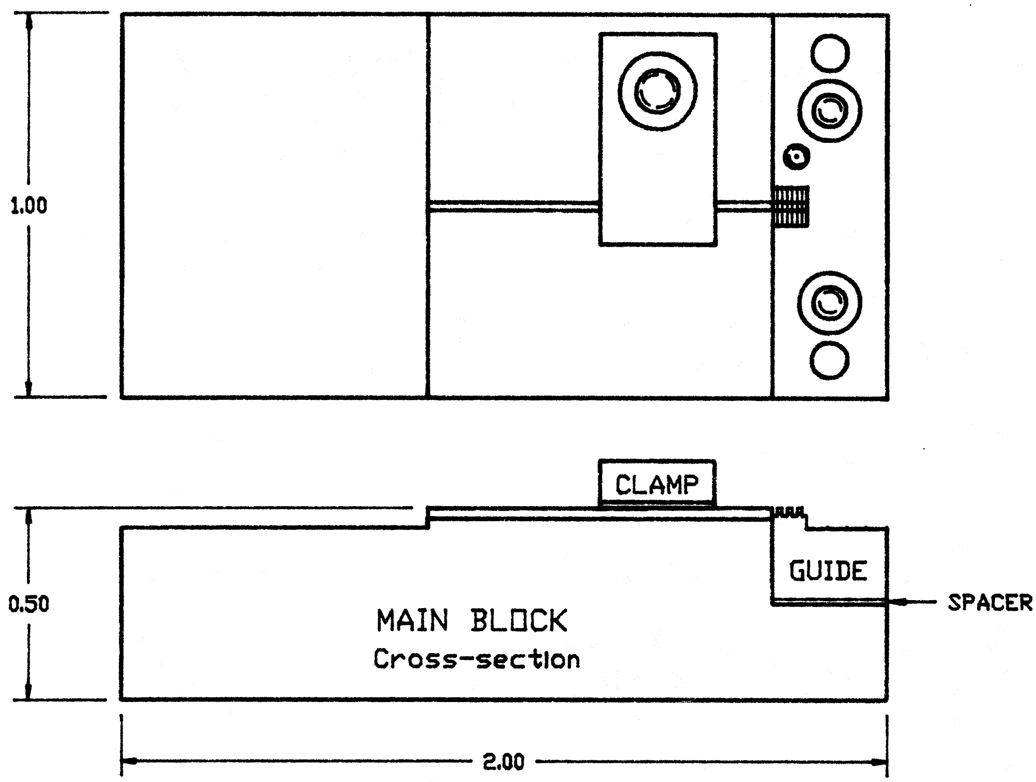
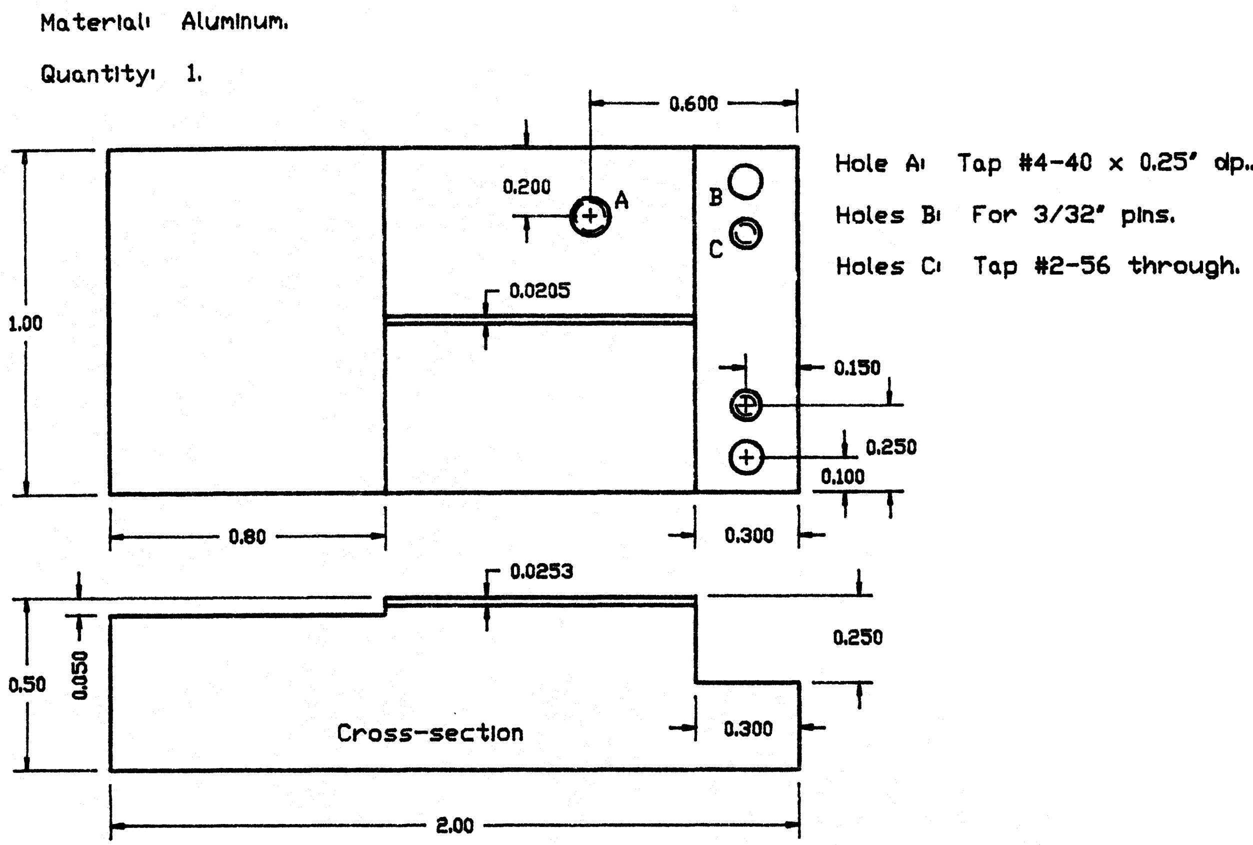
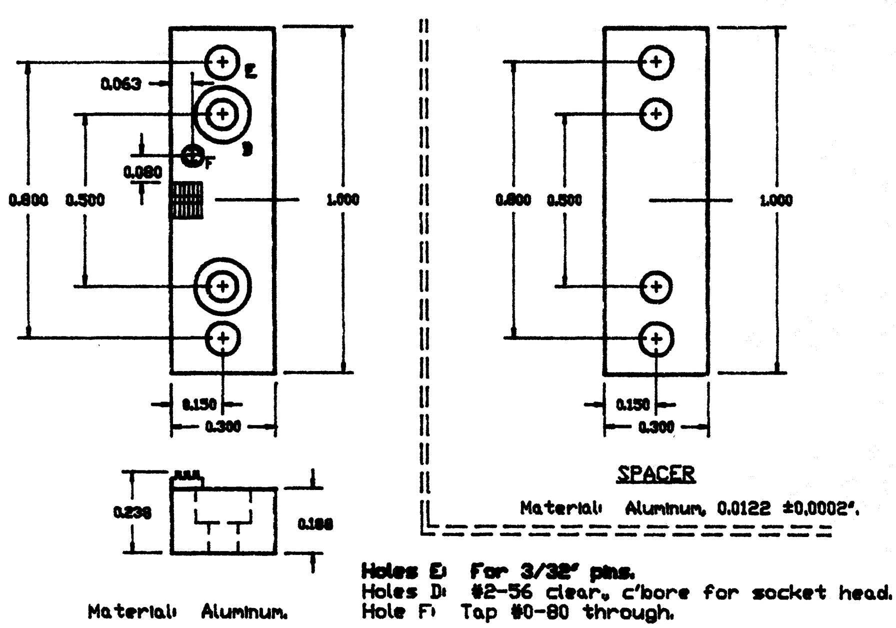


Fig. 17. Assembly fixture for the WR-4 short-circuit - see Fig. 18 for details.

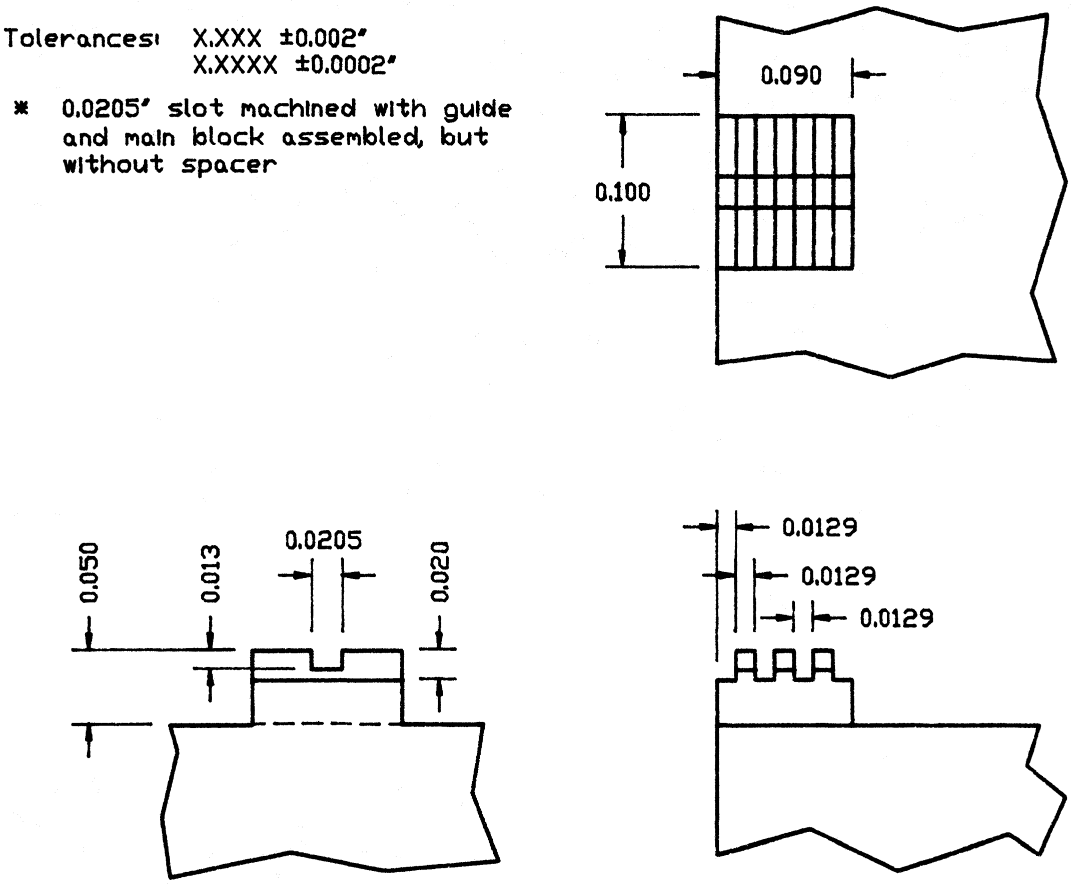


(a)

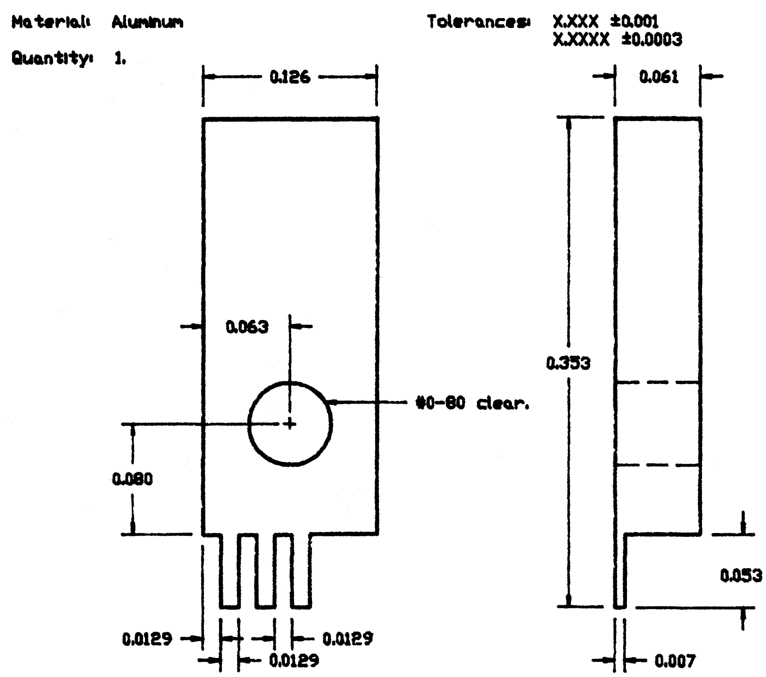


(b)

Fig. 18. Details of the WR-4 short-circuit assembly fixture shown in Fig. 17. (Continued on next page.)


Tolerances: X.XXX ±0.002"
X.XXXX ±0.0002"
* 0.0205" slot machined with guide and main block assembled, but without spacer
0.090
0.100
0.050
0.013
0.0205
0.020
0.0129
0.0129
0.0129

(c)


Material: Aluminum
Quantity: 1.
Tolerances: X.XXX ±0.001
X.XXXX ±0.0003
0.126
0.061
0.063
0.353
#0-80 clear.
0.080
0.053
0.0129
0.0129
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0.007

(d)

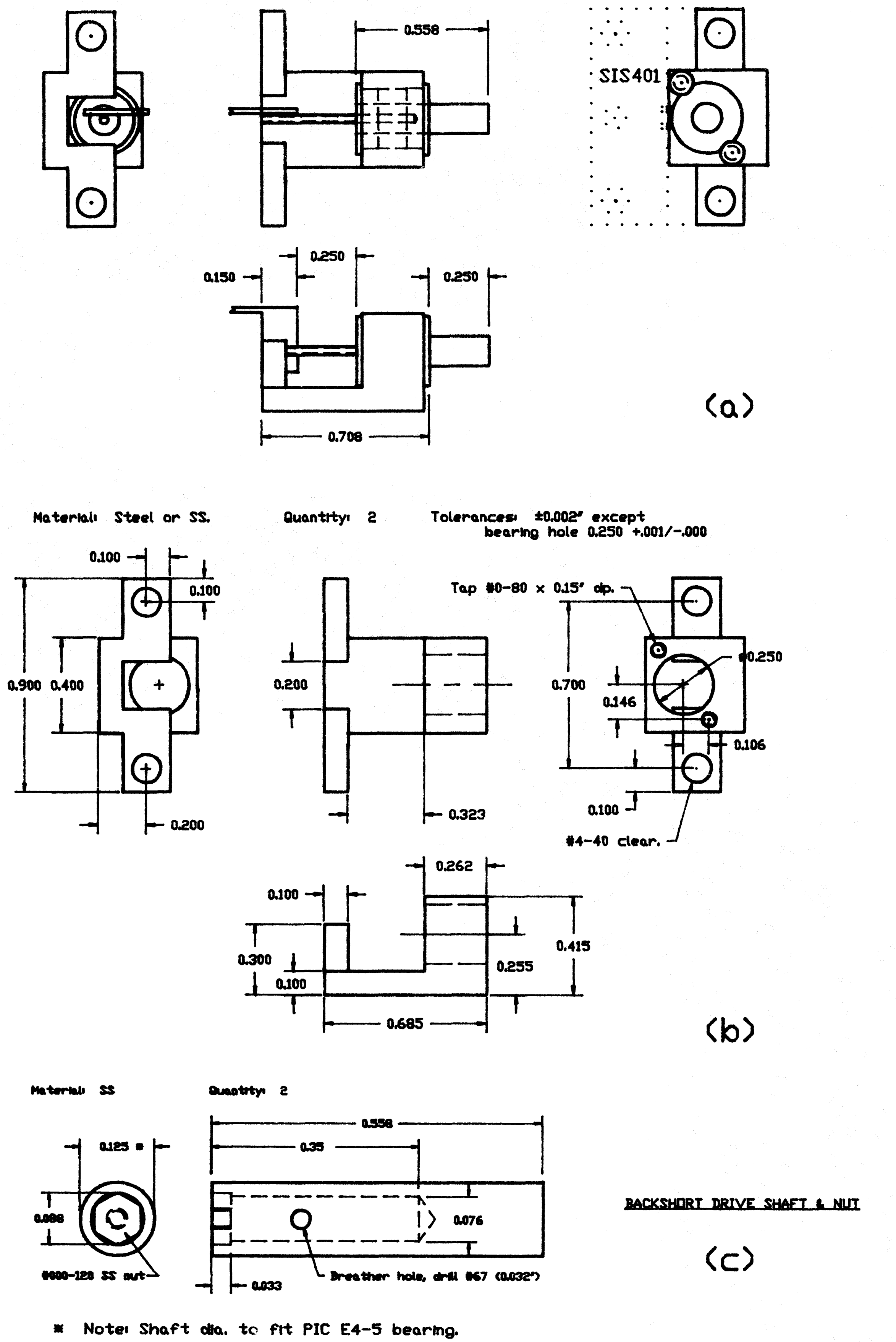

Fig. 19. Drive mechanism for the WR-4 short-circuit. (a) assembly, (b) body, and (c) drive nut. The drive shaft and nut (c) run in two ball races mounted in the body (b) which is attached to the mixer (shown dotted in (a)).