Interoffice

National Radio Astronomy Observatory

Charlottesville, Virginia

VLA ELECTRONICS MEMO #105

To: Addressee

January 26, 1973

From: R. Predmore

Subject: Circular Waveguide and Antenna Coupling for VLA IF Transmission System

I. Allowable Losses for Waveguide and Couplers

The capability to transmit 1000 MHz of information from each antenna of the VLA to the center is planned. Fourteen channels will be available for each arm and will be in the octave from 40-80 GHz. These frequencies will be transmitted in 60 mm helical waveguide which is pressurized with dry nitrogen.

The TE_{01} mode in the circular waveguide will be carrying all of the information for the VLA antennas, at least two IF signals from each antenna back to the control room, the LO signals to and from each antenna to provide a phase-locked loop, and control and monitor information. The bandwidths required for each of these signals, the expected receiver noise temperatures and transmitter powers are used in Table 1 to give the allowable losses in the TE_{01} circular WG. The receiver noise figure of 14 dB and transmitter power of -5 dBm in a 100 MHz band are achievable now at 50 GHz. In the future these will improve and these noise figures and power should be attainable at the upper operating frequencies near 80 GHz.

The allowable loss for the WG is determined by the IF signal and is about 40 dB. The losses due to the helix WG and coupler insertion loss are plotted in Figure 1.a. & 1.b. Coupled power loss is not accounted for. Figure 1.a. is a plot for losses of 1.1 and 1.5 dB/km along with 0.5 dB insertion loss per coupler. The bottom curve is for 1.5 dB/km and 0.3 dB/coupler. Due to the clustering of antenna stations near the center, the losses within 4 km are mainly determined by the insertion loss per coupler. Only for the full 21 km does the 1.1 dB/km curve show a marked departure from the 1.5 dB/km curve. Even the curves for 1.1 dB/km or 0.3 dB per coupler have more than 40 dB loss at 21 km. Consequently, in Figure 1.b. a configuration with parallel circular waveguides for the first 2 km is considered. Here the 1.1 dB/km plus 0.5 dB per coupler has a net loss of 34 dB at 21 km, which falls within the 40 dB loss budget. Also, only weak couplers, -20 to -30 dB, are required for all but the last six antenna stations. Thus, parallel IF transmission systems near the center of the array and the realization of low loss (1.1 - 1.2 dB/km) for several channels may be required to utilize the most distant antennas stations. It would be useful to study the effects on the entire array of decreasing the IF signal-to-noise ratio for a few antennas. The southeast arm of the array has 43 antenna stations, whereas the southeast and north arms only have 33 and 23 stations respectively. For a loss of 0.5 dB/coupler these arms would have 5 dB or 10 dB less attenuation than the SE arm. This decrease in attenuation for the SW and N arms makes a single transmission line with all couplers installed more feasible.

II. Octave Bandwidth Couplers

In order to maintain the integrity of the dry nitrogen pressurization system for the circular WG and to allow for quick antenna connect and disconnect it is necessary to leave the couplers in the main line. This requires that the coupler have a low insertion loss across the 40-80 GHz band and that the coupler be broad-band so that it could be used for many different channels. If possible a coupler covering the entire octave (40-80 GHz) is needed.

Two methods for achieving the octave bandwidth while maintaining low insertion loss for the main line are the figure-8 coupler or a beam splitter type of coupler. A figure-8 coupler is shown in the Figure 2. Ports 1 and 2 are in the main line and port 4 is where power is coupled into or out of the main transmission system. Both circular waveguides have the same diameter so that they have the same propagation constants.

In designing a figure-8 coupler, there are three parameters, the waveguide diameter, the coupling hole diameter, and the thickness of the wall between the two waveguides. Increases in wall thickness decreases the coupling since the wave in the coupling hole is below cutoff. However, this effect does not have a strong frequency dependence, so a minimum thickness ($\simeq$ 0.3 mm) which is compatible with manufacturing is chosen.

Figure 3 illustrates the effect on the amplitude coupling coefficient of changing the coupling hole diameter for a 10 mm diameter waveguide. The wave in the circular coupling hole is below TE_{11} cutoff and as the frequency approaches the cutoff frequency f_{11} (GHz) = 175.8/d(mm), the coupling becomes stronger. The coupling for the smaller holes, i.e., 1.5 mm, is more uniform with frequency since 80 GHz is far below the cut-off frequency of 117 GHz. Figure 4 shows the variation of the coupling coefficient with changes in the diameter of the circular waveguides. The strongest effect in absolute coupling strength is a D^{-4} dependence; however, since at 40 GHz the smaller diameter waveguides are nearing the TE_{01} cutoff f_{01} (GHz) = 366/D(mm) there is a large increase in guide wavelength as frequency decreases. This gives a strong frequency dependence to the relative coupling strength. For $D > 15$ mm, and the small coupling hole diameter used in Figure 4, the coupling variation is only 3 db over the octave from 40-80 GHz.

Then the total coupler design the over-length of the coupler must be considered. In order to maintain good directivity the hole spacing must be

$$S < \lambda min/2$$

where λmin is the shortest wavelength at which the coupler will be used. If the coupler is used at 80 GHz, $S < 1.8$ mm. This will limit the coupler hole size and increase the coupler length somewhat.

Figure 5 relates the number of coupling holes and the coupler length versus coupled power for various waveguide diameters. The hole diameter is 1.2 mm, and the frequency is 60 GHz. Even for a coupling of -40 dB waveguides with $D > 20$ mm become longer than 300 mm. For stronger coupling (up to -20 dB) a coupler with 15 mm diameter should be suitable while covering an octave band.

The theoretical loss in a circular waveguide varies as

$$L \cdot D^{-3} f^{-3/2}, \text{ where}$$

L is the waveguide length, D is the diameter and f is the operating frequency. In a figure-8 coupler the coupling per unit length varies as D^{-4}. Consequently for a fixed coupling value $L \propto D^{+4}$. Consequently the net effect on coupler resistive losses is that loss varies as the Diameter. Thus larger diameter couplers theoretically have higher losses. For a TE_{01} circular to TE_{10} rectangular coupler the coupling $\propto D^{-2}$. Consequently L only varies as D^{2}, and loss $\propto D^{-1}$. However, Furukawa's 11 mm coupler losses should only be 0.06 dB at 50 GHz and are actually 0.4-0.5 dB, so effects other than resistive losses are quite significant. These losses need to be understood before the coupler design can be chosen.

III. Beam Splitter Coupling

With a beam splitter coupler the coupler power is reflected from a plane dielectric sheet out of the main waveguide into a side arm. As shown in Figure 6, the dielectric sheet is at 45° with respect to the incident and reflected waves. An insertion loss of 0.5 dB over the 50-60 GHz was obtained in 1960 by Marcatili and Bisbee (Bell System Technical Journal, Vol. 40, 1961, p.197-212). We have discussed beam splitter couplers with H. C. Wang of Bell Labs, North Andover, Mass. His work indicates that diffraction losses are ≈ 0.3 dB whatever the coupling and that insertion losses from coupling to other modes is 0.12 dB for a -18 dB coupler. This coupling was obtained with a dielectric foam sheet with $\varepsilon_r = 1.3$. Thinner sheets may give weaker couplings. Couplers between -3 dB and -20 dB can be made by modifying the dielectric constant and thickness of the beam splitter. Insertion losses should be 0.4 to 0.5 dB. The low insertion loss and broad-band, almost uniform coupling of beam splitter couplers make them a very promising choice for the VLA IF transmission system.

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VLA Distribution List

TABLE 1. POWER AND LOSS BUDGET

Signal	Bandwidth	KTB Noise (dBm)	Receiver Noise Figure (dB)	Noise (dBm)	S/N (dB)	Signal Level (dBm)	Trans. Power (dBm)	Max. Loss	Extra Loss	WG Loss
IF	100 MHz†	- 94	14	- 80	20	- 60	- 5	55	15	40
1 GHz LO	10 kHz	-134	14	-120	50	- 70	-10	60	20	40
100 MHz LO	1 kHz	-144	14	-130	50	- 80	-20	60	20	40
Control & Monitor	100 kHz	-124	14	-110	30	- 80	-20	60	20	40

†Present Bandwidth for each of two channels from each antenna. Future plans are for a 1000 MHz total information bandwidth from each antenna.

[redacted] AUDIO FREQUENCY [redacted] KEUFFEL & ESSER CO.

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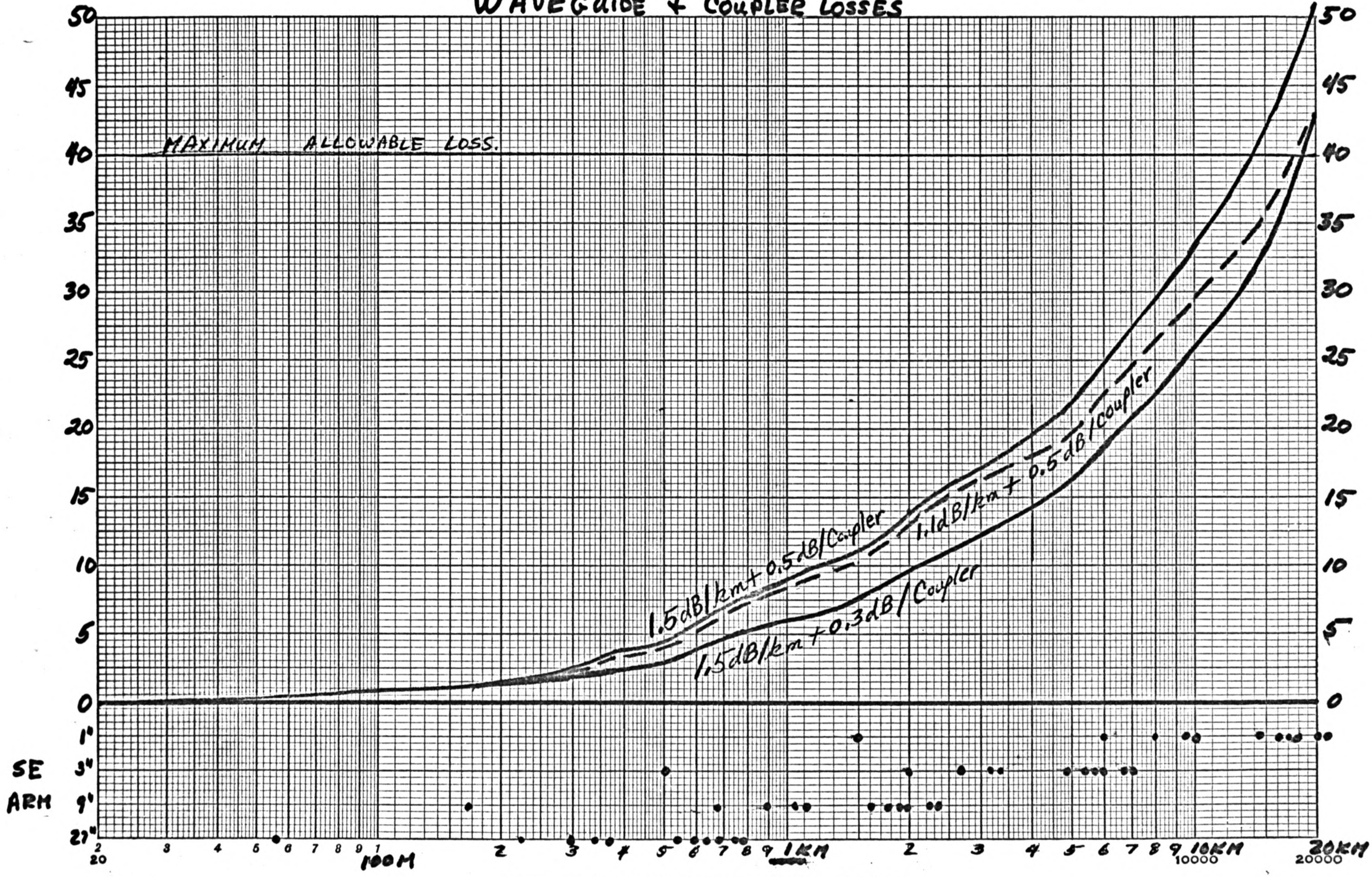
WAVEGUIDE + COUPLER LOSSES



~~FREQUENCY IN CYCLES PER SECOND~~

DISTANCE FROM THE CENTER OF THE VLA.

FIGURE 1.a

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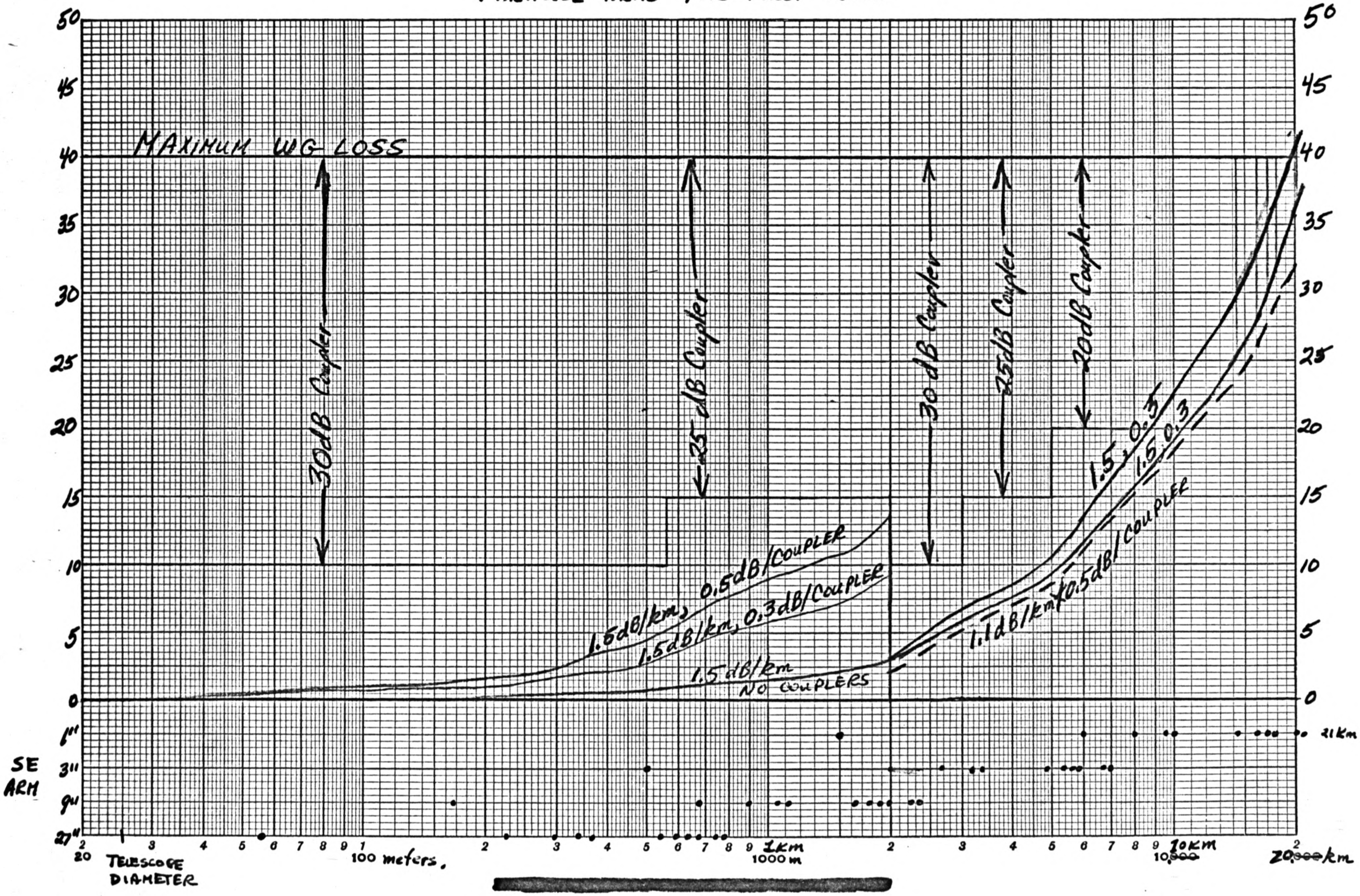
WAVEGUIDE + COUPLER LOSSES
PARALLEL ARMS FOR FIRST 2KM.



DISTANCE FROM THE CENTER OF THE VLA.

FIGURE 1.b

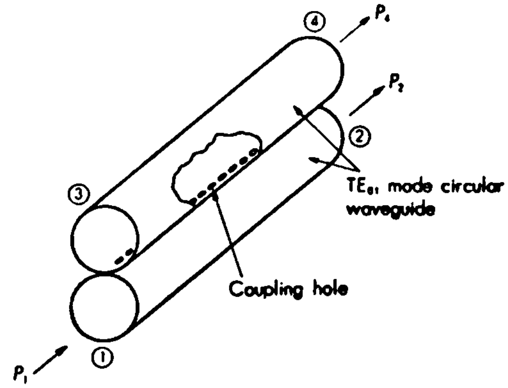


Fig. 2—Fundamental structure of figure-8 hybrid.

Effect of Coupling Hole Diameter

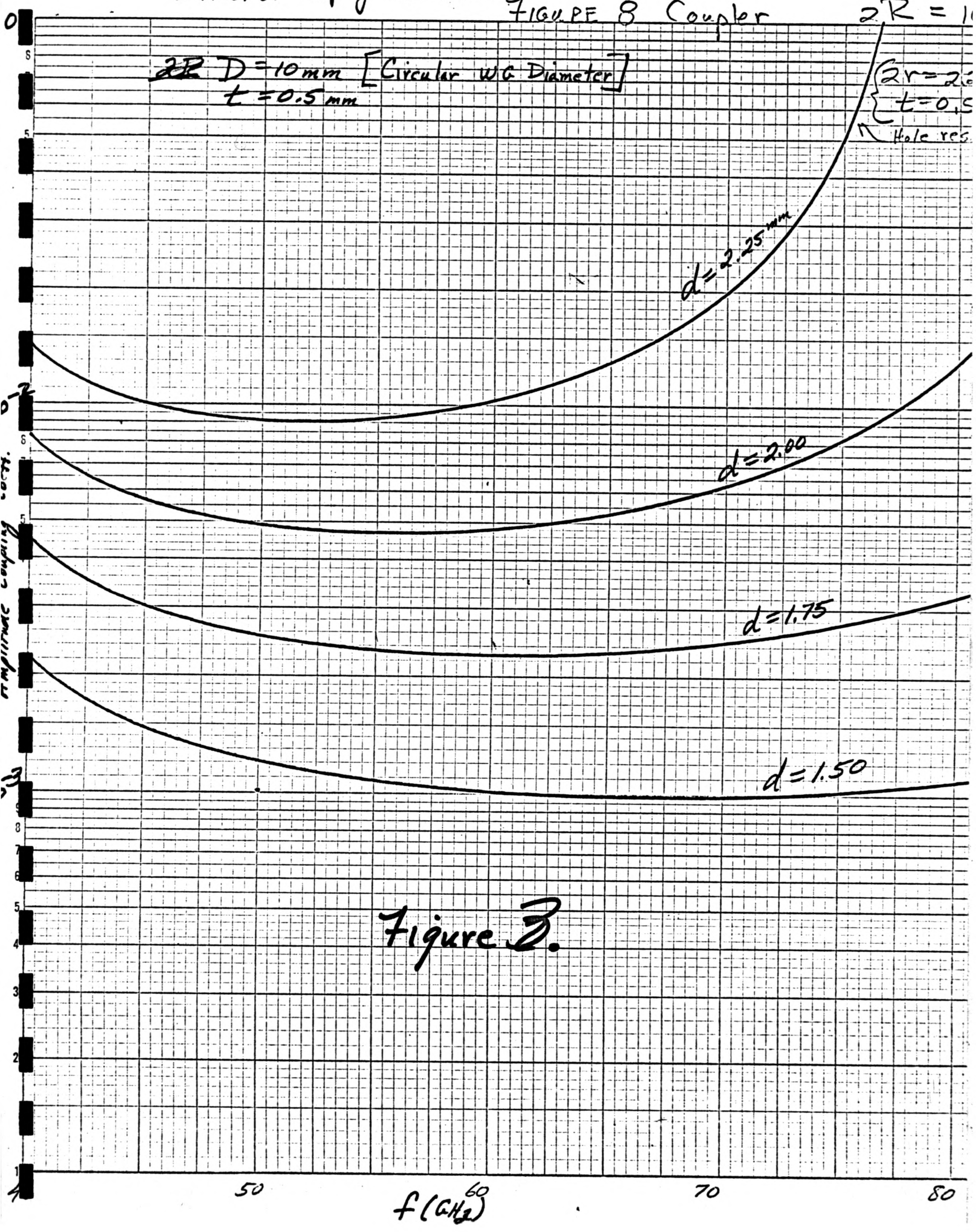
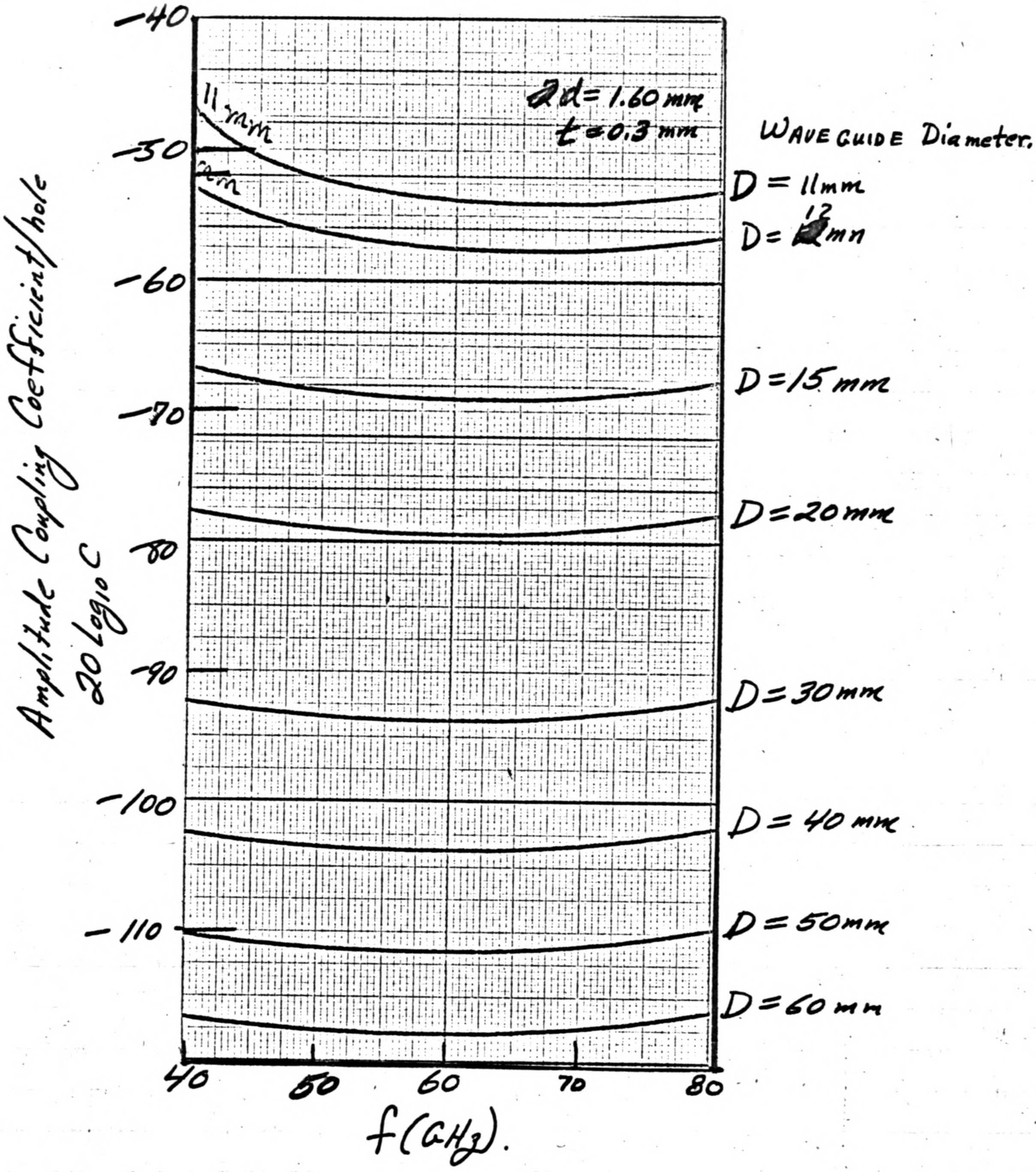


Figure 3.

Figure 8 Coupler



Coupled Pwr (dB) = $20 \log_{10} C + 20 \log_{10} N$

where **N** is the number of Coupling Holes.

FIGURE 4.

Number of Coupling Holes For Figure 8 Coupler.

Hole diameter = Ø1.2mm
Wall Thickness t = 0.3mm
Frequency = 60GHz.

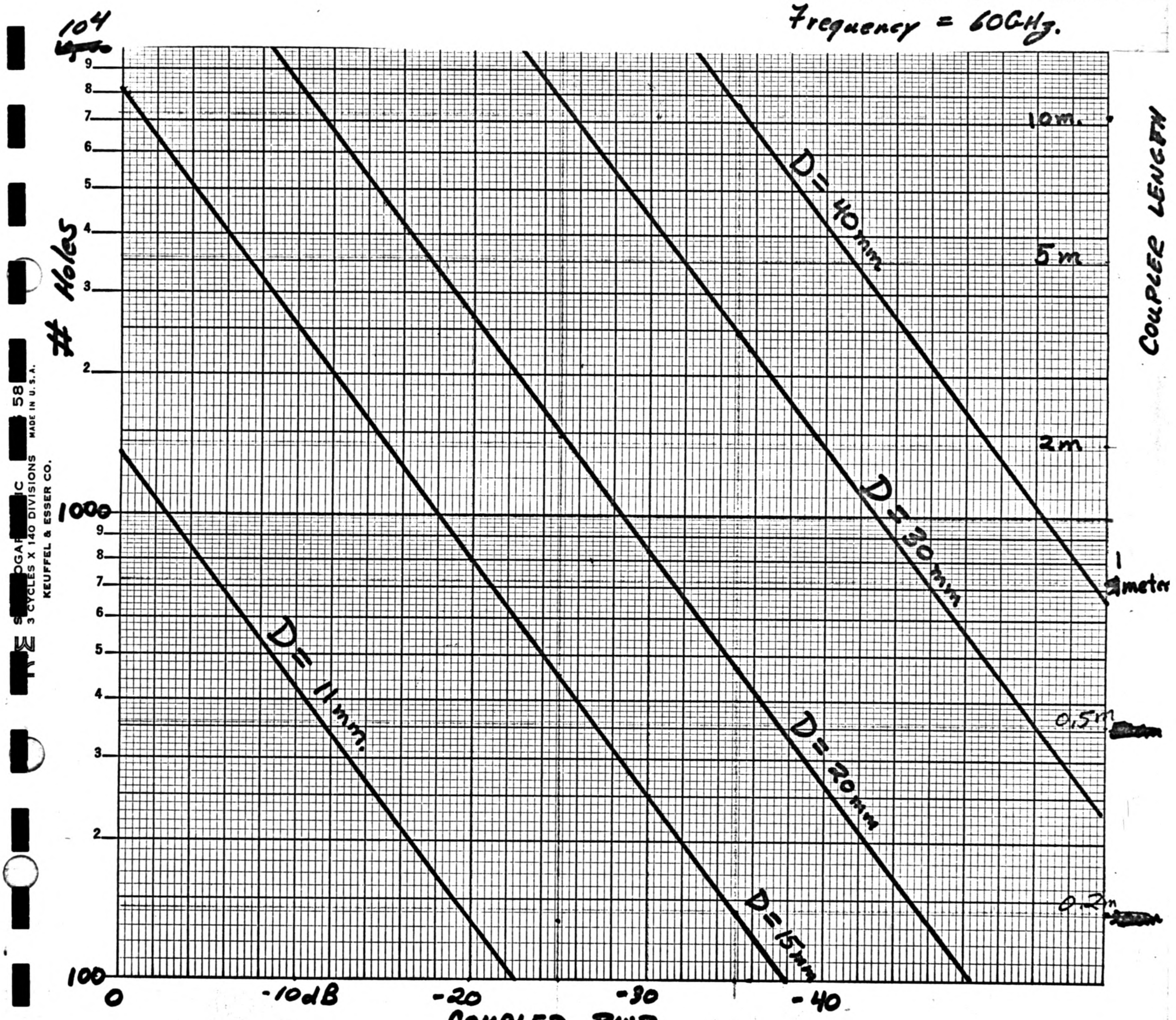


FIGURE 5

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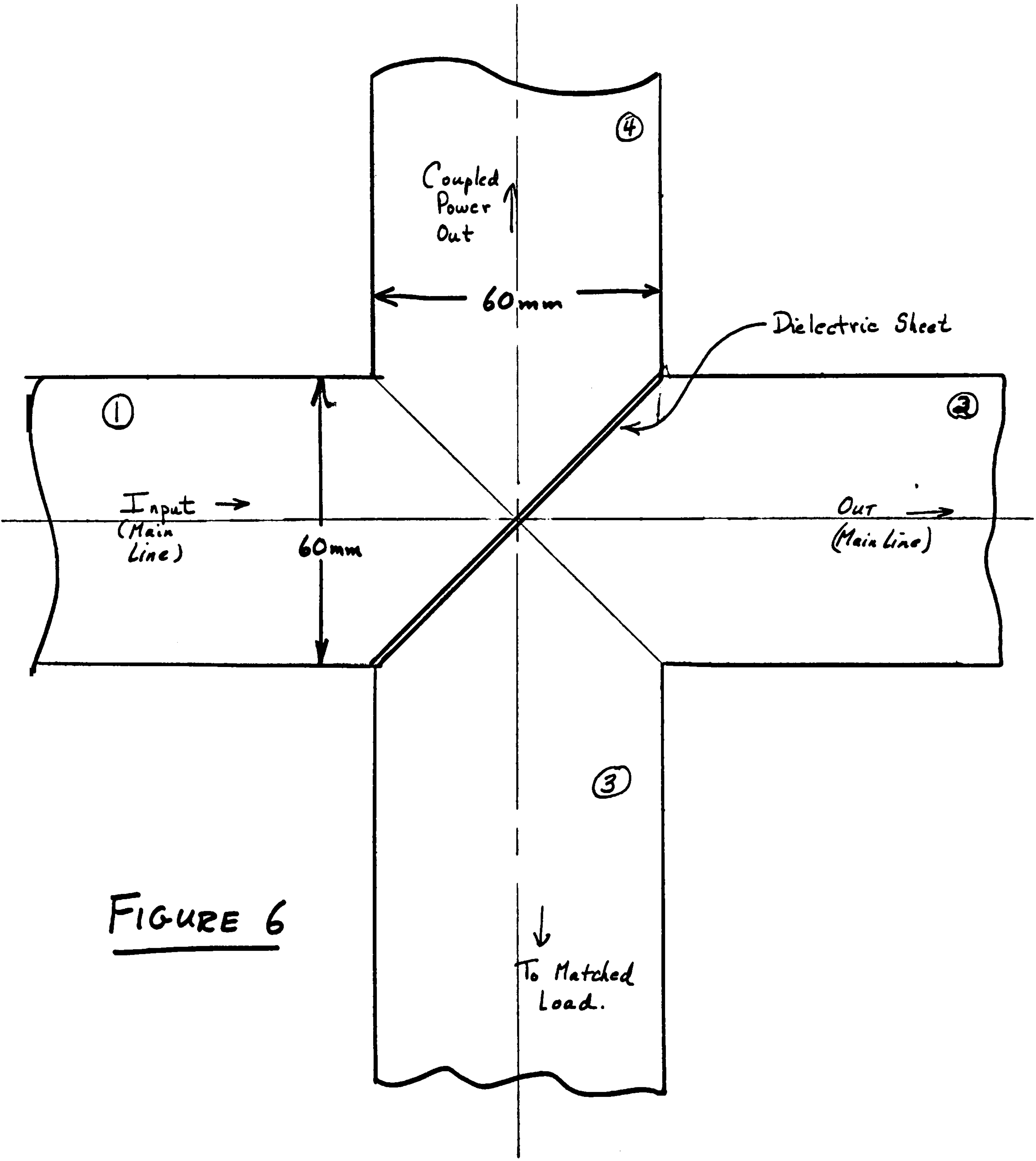

FIGURE 6