A Millimeter-Wave Directional Filter Cavity

BRAD D. MOORE, STUDENT MEMBER, IEEE, AND JOHN R. COGDELL, MEMBER, IEEE

Abstract—**The theory and design of millimeter-wave directional filter cavities are presented. Experimental results obtained at 15 and 100 GHz are described.**

I. Introduction

As LONG AS low-noise amplifiers are not generally available at millimeter wavelengths, the mixer will continue to be a critical component in determining system noise temperature. One important aspect of receiver design is the supplying of local oscillator (LO) power to the mixer. In the case of balanced mixers, the LO power can be combined with the signal power in a hybrid structure. However, in single-ended mixers, which are commonly used at millimeter wavelengths, the LO power is combined with the signal external to the mixer in a three-port structure. Desirable features for such a structure include the following:

1) low attenuation between LO input and output (to mixer) at LO frequency;
2) good isolation between LO input and signal input;
3) low attenuation between signal input and output at the signal frequency;
4) high attentuation between LO input and output at the signal frequency.

These features result from the requirement for coupling the LO and signal powers to the mixer with minimum loss while minimizing the coupling of the LO noise spectrum. The necessity for this feature is illustrated in Fig. 1, which shows the noise spectrum typical of a 100-GHz reflex klystron [2]. Since the mixer receives two sidebands, the klystron noise contribution to the SSB system temperature is approximately 2×10^4K times the isolation between the klystron and the mixer input for intermediate frequencies (IF's) in the range 1–2 GHz. If coupling is accomplished through a resonant structure, this places restrictions on the Q of the structure. Also, we find that a transmission cavity's response departs from the ideal resonance curve and quickly reaches a coupling which is independent of frequency. This off-resonance isolation needs to be greater than 30 dB for the case we have described previously and should be higher if the IF is lower.

Directional couplers, injection cavities, and resonant rings have been used in millimeter receivers to couple LO power to the mixer. These structures compromise one or more of the desirable characteristics which we have listed. The present work describes the development of an injection cavity which potentially satisfies all the criteria. The structure shown in Fig. 2 consists of a cylindrical coupling cavity placed between two parallel waveguides. Circular coupling holes or irises are placed off axis on the waveguides and couple to the transverse and longitudinal magnetic fields in the dominant mode. The irises are located such that the magnetic field is approximately circularly polarized and thus couple to a circularly polarized mode in the cavity. Thus the output waveguide is excited directionally, and ports A and D are decoupled for proper iris location. Ports A and B can be approximately decoupled by proper choice of coupling iris size [4], thus making excellent coupling between ports A and C. Our cavity is similar to that proposed by Nelson [4] except that both coupling irises are placed in the same end of the cavity, leaving the other end free as a tuner.

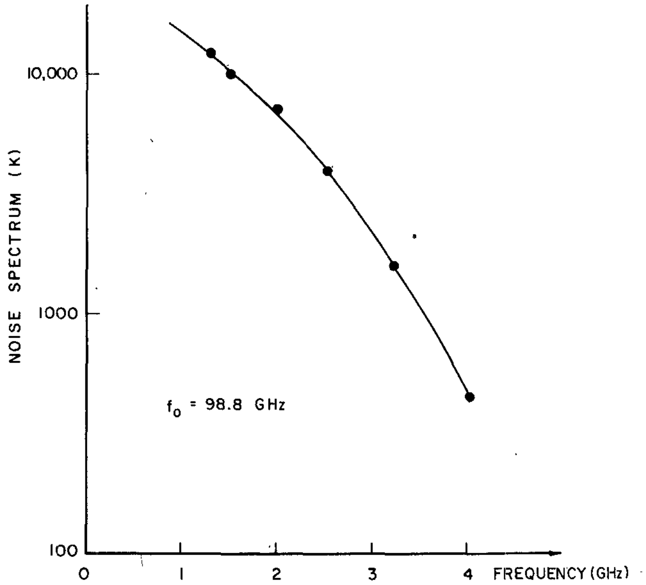

Fig. 1. Measured noise spectrum of a 100-GHz reflex klystron.

The cavity mode excited is the TE_{111}. In our early work we supposed that the cavity would not support the TE_{111} mode because of the movable end plate, but we discovered rather early that choke rings on the end plate gave sufficient termination to the fields to give an adequate cavity Q in this mode.

II. Design Theory

A. Coupling Iris

The simplest case to analyze is that where the iris is on the axis of the cavity. Although this is not physically realistic because we require two irises, it will be considered as a first step in the analysis. From the viewpoint of the cavity, an iris on the axis will couple perfectly to the TE_{111}

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B. D. Moore was with the Electrical Engineering Research Laboratory, University of Texas, Austin, TX 78712. He is now with the Motorola Government Electronics Division, Scottsdale, AZ.
J. R. Cogdell is with the Electrical Engineering Research Laboratory, University of Texas, Austin, TX 78712.

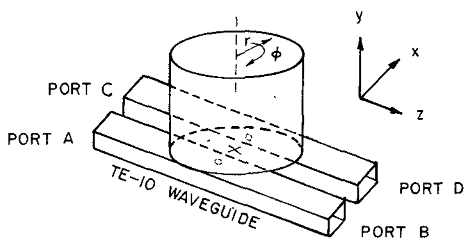

Fig. 2. Four-port transmission cavity.

circular mode if the hole is located relative to the waveguide where the polarization of the TE_{10} magnetic field is circular, i.e., where $|H_x| = |H_z|$. This location is easily shown to be

$$d = \frac{a}{\pi} \arctan (\lambda_g/2a) \tag{1}$$

where

- a waveguide width;
- d coupling hole distance from narrow wall of waveguide for circular polarization;
- λ_g guide wavelength.

Clearly, the geometry does not permit the coupling irises to be located on the cavity axis, since two holes are required, and we must therefore consider off-center holes in the cavity. This involves exciting elliptical polarization in the cavity and is best thought of in terms of two linear couplings: an $H_x \to H_r \to H_x$ coupling [Fig. 3(a)] and an $H_z \to H_\phi \to H_z$ coupling [Fig. 3(b)]. The phase relations which can lead to cancellation between ports A and D are unchanged by moving the irises off center; therefore the requirement for directional coupling is that [3]

$$H_x(d')H_r(r_i) = H_z(d')H_\phi(r_i) \tag{2}$$

where d' is the hole location relative to the waveguide (no longer d), and r_i is the hole location relative to the cavity (see Fig. 4). Substitution of the field equations in (2) results in

$$d' = \frac{a}{\pi} \arctan \left[\frac{\lambda_g}{2a} \frac{J_1(\alpha)}{\alpha J_1'(\alpha)}\right] \tag{3}$$

where J_1 is the first-order Bessel function and J_1' is its derivative, $\alpha = 1.84 r_i/r_0$, and r_0 is the cavity radius. This equation may be solved for the correct hole location, given that either r_i or d' is specified. Clearly, only solutions where $r_i > (D/2) + (t/2)$ produce realizable results (Fig. 4), where D is the iris diameter, and t is the thickness of the wall between the waveguide.

B. Iris Size

The coupling of wave structures through small iris was investigated by Bethe [1] and applied to cavity/waveguide coupling by Slater [5], Nelson [4], Williams [6], and others. The results can be expressed in terms of a window coupling Q_w, which is derived from the power passed by the iris normalized to the stored energy in the cavity. For the present structure, the overall Q would be [4]

$$\frac{1}{Q_L} = \frac{1}{Q_c} + \frac{1}{Q_w} \tag{4}$$

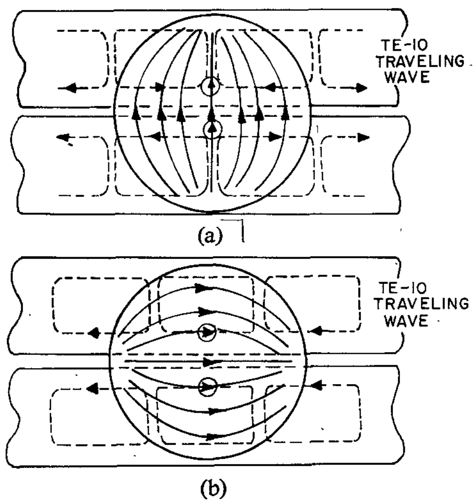

Fig. 3. Waveguide TE_{01} and cavity TE_{111} magnetic-field coupling. (a) $H_x \to H_r \to H_x$ coupled TE_{111} mode. (b) $H_z \to H_\phi \to H_z$ coupled TE_{111} mode.

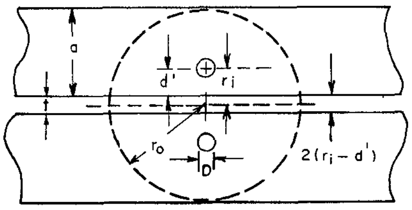

Fig. 4. Dimensions of off-centered irises.

where Q_L is the loaded Q of the cavity, Q_c is the unloaded Q of the cavity from wall and end plate leakage losses, and Q_w is coupling Q from a single hole. The coupling between a TE_{10} waveguide and a TE_{111} cavity was presented by Williams [6] based on Bethe's work [1], as

$$Q_w(0) = \frac{27 a^3 b r_0^2 \lambda_g'^3}{4\pi\lambda_0^2 \lambda_g D^6 \cos^2 (\pi d'/a)} \tag{5}$$

where b is the waveguide height, λ_0 is the free-space wavelength, and

$$\lambda_g' = \text{cavity wavelength} = \left[\frac{1}{\lambda_0^2} - \left(\frac{1}{3.4/r_0}\right)^2\right]^{-1/2}.$$

The expression in (5) is derived for the on-axis iris ($r_i = 0$) and must be modified for off-axis irises by the factor

$$Q_w(r_i) = \frac{Q_w(0)}{[2J_1'(\alpha)]^2} \tag{6}$$

where $2J_1'$ is the magnetic field at the iris normalized to the value at the cavity axis.

The effect of finite iris thickness is not negligible at millimeter wavelengths. This effect may be approximated by considering the iris a cutoff circular waveguide transmitting power in the cutoff TE_{11} mode. This will increase Q_w by a factor A,

$$A = \exp \{4\pi\delta(1/\lambda_0^2 - 1/\lambda_c^2)^{1/2}\} \tag{7}$$

where δ is the iris thickness and λ_c is the cutoff wavelength of the iris $(=1.706D)$. The various factors may be combined to yield

$$Q_w(r_i,\delta) = Q_w(0)A/[2J_1'(\alpha)]^2. \tag{8}$$

Equations (8) and (4) give the loaded Q_L of the cavity.

The coupling through the cavity can be expressed in terms of the cavity Q's and the iris thickness attenuation. Nelson [4] shows that in the absence of iris thickness attenuation, the coupling between ports A and C can be expressed as

$$\frac{P_c}{P_A} = \left(1 - \frac{Q_L}{Q_c}\right)^2. \tag{9}$$

The unloaded Q_c of the cavity for the case where the end plates and cylindrical surfaces are constructed of different materials can be calculated from

$$Q_c = \frac{1 + 0.343\left(\frac{L}{r_0}\right)^2}{2\frac{\delta_e}{L} + 0.419\left(\frac{\delta_c}{r_0}\right)\left[1 + 1.163\left(\frac{L}{r_0}\right)^2\right]} \tag{10}$$

where

L cavity length $(=\lambda_g'/2)$;
δ_e skin depth for the end plates;
δ_c skin depth for the cylindrical walls.

For the case where the end plates are different, as in the cavities discussed later, the first term in the denominator can be divided into two terms, one for each end plate. The various equations in this section permit the calculation of transmission loss, loaded cavity Q, and iris location as a function of iris diameter and thickness. Investigation of possible cavity design shows that it is possible to build cavities with acceptable properties. Fig. 5 shows the results of solving (3) and (8), for the case of the 15-GHz cavity to be discussed in the next section.

III. Experimental Work

A. 15-GHz Cavity

A cavity was constructed and tested at 15 GHz in order to test the preceding theory. An exploded view of the cavity is shown in Fig. 6. The waveguides were milled in an aluminum block and the coupling irises were drilled in 0.035 and 0.005-in-thick brass shim stock, which was clamped between the waveguide block and the cavity body. The dimensions chosen were $r_0 = 0.75$ in, $r_i = 0.167$ in, and $d' = 0.134$ in. Cavity performance was investigated for various iris diameters. The results are shown in Fig. 7, along with calculated losses for $Q_c = 3110$, the value fit to the data. This is to be compared with a value of 6000 calculated from (10). The least transmission loss ashieved was 0.7 dB with a 0.005-in shim. Directionality was in excess of 20 dB.

Two problems were encountered with this cavity. The mechanical contact between the shim and the rest of the structure was not always good, and this resulted in unrepeatable measurements. The scatter in the data shown in Fig. 7 appeared to be due to this problem. When the mechanical contact with the shim was good, the off-resonance isolation was good, in excess of 40 dB, but when the shim made poor contact with the waveguide block, the direct leakage between the adjacent waveguides made for poor off-resonance isolation.

The second problem encountered was due to a dual

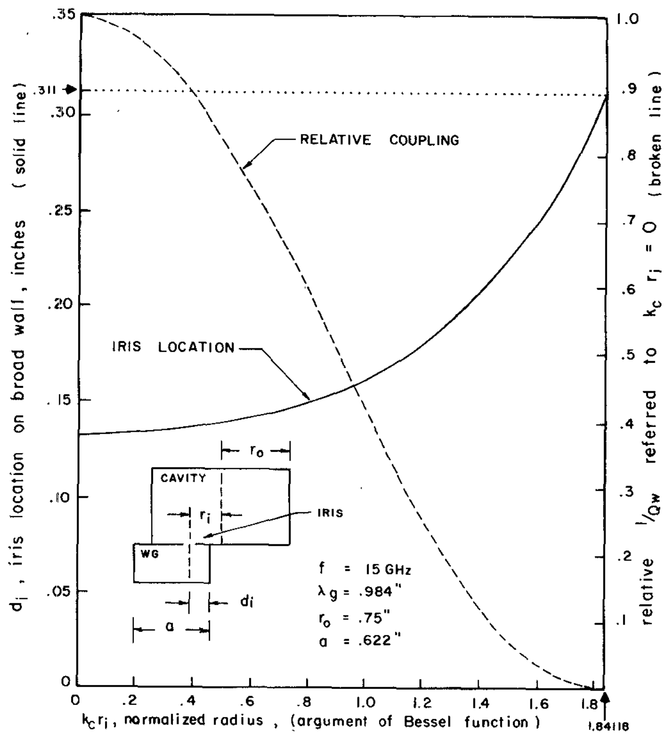

Fig. 5. Plot of (3) for 15-GHz cavity and relative coupling versus iris location.

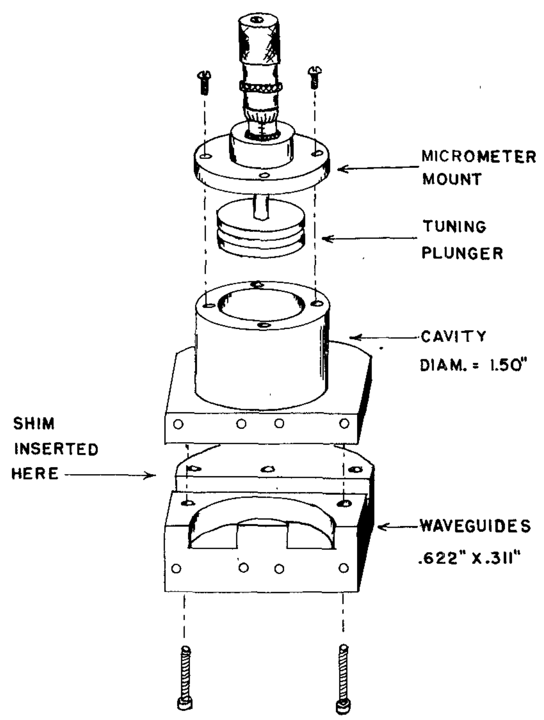

Fig. 6. Exploded view of 15-GHz cavity.

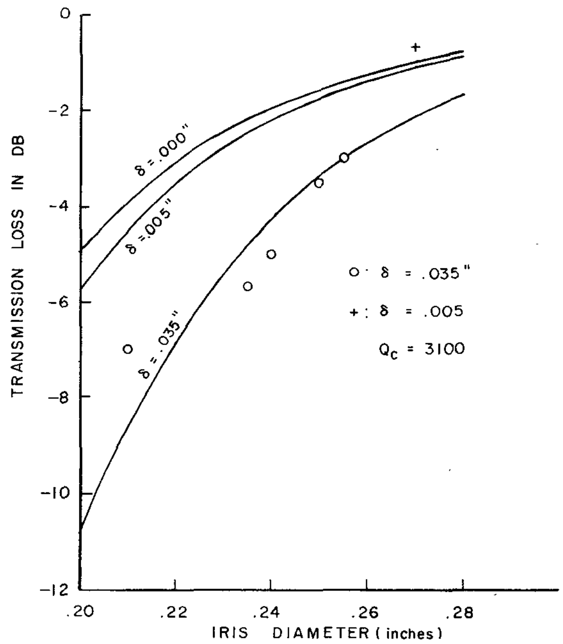

Fig. 7. Measured transmission loss for 15-GHz cavity.

resonance effect. The circular TE_{111} mode can be thought of as two linear TE_{111} modes in a quadrature phase relation. In the original cavity these two modes were at slightly different frequencies and thus cavity performance was degraded. This problem was solved by placing two tuning screws at right angles in the cavity wall.

The best performance of the 15-GHz cavity was 0.7-dB insertion loss, 20-dB isolation, and off-resonance isolation in excess of 40 dB. Although this performance was unrepeatable due to the problems mentioned previously, it effectively confirms the validity of the basic principles and design approach.

B. 100-GHz Cavity

A second cavity was constructed with RG 138 waveguide (Fig. 8). This cavity used a photo-etched 0.005 copper shim. The dimensions of the cavity were $r_0 = 0.100$ in, $r_i = 0.038$ in, $d' = 0.023$ in, and $t = 0.030$ in. The separation between the waveguides was chosen relatively large because of difficulties in machining the coin silver from which the cavity was constructed. The tuning end plate was machined with choke rings and rounded in one direction to permit tuning of the split modes (by rotating the entire micrometer assembly). This rounding of the tuner was more extreme than was desirable due to a considerable separation of the modes, and in the end it was evident that the unloaded Q of the cavity was lowered by the leakage around the tuner. Scaling laws favored better mechanical stability for this cavity than for the larger cavity, and the principal problem was the splitting of the modes, as described previously.

The cavity was tested at 100 GHz with an iris diameter of 0.035 in. The best performance was as follows: insertion loss—4.4 dB, directionality—13 dB, and off-resonance isolation—44 dB. This implies an unloaded cavity Q_c, including waveguide losses of 1200, which compares to a calculated unloaded Q of 2500. Thus we obtain reasonable

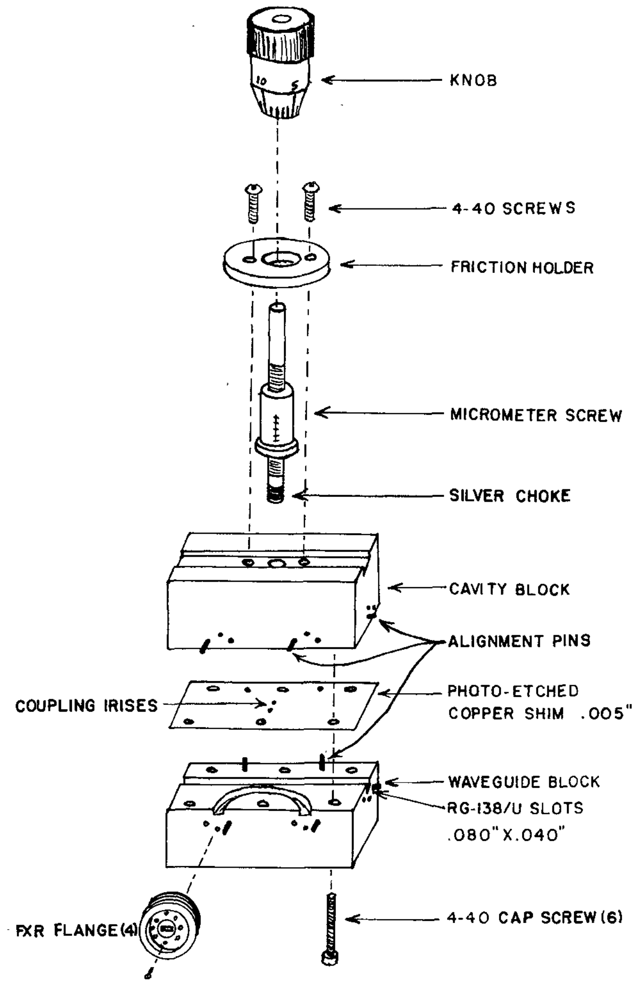

Fig. 8. Exploded view of 100-GHz cavity.

agreement between the theory and the cavity performance. Reducing the iris thickness to 0.001 in could further reduce loss to about 2.5 dB, and polishing of the cavity and waveguide would lend further reductions in the cavity losses.

The detuning of the modes appears to be due to the loading of the irises on the cavity fields. Using Bethe's expression, we calculate a detuning of 1.7 GHz for the difference in the resonant frequencies of the modes, and we measure a detuning of 0.5 GHz with an unrounded tuning plunger. This disagreement is to be expected since the narrow height of the cavity ($\approx \lambda_0/2$) does not permit the perturbation fields to be fully developed, as Bethe's expression requires. In future development work, we will experiment with elliptical irises, so that the detuning will be canceled to first order.

IV. Discussion

The theory and construction of millimeter-wave directional filter cavities have been described. While the principles of operation are similar to those described by Nelson [4], the particular realization of the cavities described offers advantages in construction and the important feature of tunability. The measured performance of the 100-GHz cavity is satisfactory for use as an injection cavity in a millimeter receiver.

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Helical Coupler from Rectangular-to-Circular Waveguide

C. READ PREDMORE, MEMBER, IEEE

Abstract—**The very-large-array (VLA) radio telescope utilizes a low-loss TE_{01} circular waveguide transmission system. During the design of this system a coupler was developed which couples directly from a standard millimeter rectangular waveguide to the TE°_{01} mode in highly overmoded circular waveguide. In contrast to previous couplers which used periodically spaced groups of coupling holes, this design wraps the rectangular waveguide in a helix around the circular waveguide to give a continuous array of coupling apertures for maximum coupling and a compact mechanical configuration. The helix angle is chosen to match the phase velocities of the rectangular and circular waveguide modes at a given frequency. In particular, couplers have been designed and fabricated which couple from WR-28 (26.5–40-GHz) and WR-22 (33–50-GHz) rectangular waveguides to the TE°_{01} mode in 20- and 60-mm-diam circular waveguide.**

I. INTRODUCTION

THE very-large-array (VLA) radio telescope, presently being constructed near Socorro, NM, will combine the signals from 27 paraboloid antennas. The antennas are each 25 m in diameter and are arranged in a Y-shaped pattern to provide the optimum sky coverage [1]. Nine antennas will be placed on each arm of the Y at distances from 40 m to 21 km from the intersection of the three arms. There are 24 fixed locations on each arm for various observing configurations, with 14 of those stations being within 2 km of the center. All of the antennas on an arm are connected to the control building near the center of the array by a single TE°_{01} mode transmission system. This low-loss mode is achieved in a 60-mm-diam circular waveguide which has a helix lining of enameled copper wire for spurious mode suppression [2]–[4]. This waveguide mode has been studied for a number of decades [5] but has been brought to the production stage only recently in Japan and the United States [6].

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The author was with the National Radio Astronomy Observatory, Socorro, NM. He is now with the Department of Physics and Astronomy and the Department of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA 01002.

Each antenna transmits local oscillator tones and a 200-MHz band received from astronomical sources to the control room in a 1-GHz band at a fixed frequency between 26 and 52 GHz. Weinreb *et al.* [7] describe the waveguide system in more detail. Since the losses in the circular waveguide are only 2.2–1.2 dB/km, between 26 and 52 GHz, the waveguide losses for the first 14 stations are less than 5 dB. Consequently, directional couplers with only loose coupling are required at those inner stations. It was desired to leave the couplers in place when the outer ten stations were being used. Since signals from those stations must propagate through the inner stations, the coupler insertion loss, return loss, and TE°_{0n} $(n > 1)$ mode generation must be quite good. Section II discusses the desired characteristics for coupling into the 60-mm waveguide and matches the possible coupler types to the system requirements. In Section III the helical coupler design will be discussed. Then the experimental results for 20- and 60-mm helical couplers will be presented.

II. DESIGN CRITERIA

The observing positions for the VLA antennas are clustered near the center of the Y with the first 14 stations within 2 km of the center. Beyond 2 km the spacing between stations increases from 400 m to 4 km. The waveguide loss is low so that no repeaters are required over the 21-km length. But, since the low loss does not dampen out interactions between system components such as couplers, which may be kilometers apart, the characteristics of the system components must be well chosen. Since the helix-lined waveguide will filter out TE°_{mn} $(m > 0)$ and TM°_{mn} modes with a loss of >2000 dB/km, the prime considerations are the TE°_{01} return loss and the TE°_{01}–TE°_{02} mode generation for a wave going through a coupler.

A coupler with an inner diameter the same as the rest of the circular waveguide will minimize these quantities since reflections and TE°_{0n} $(n > 1)$ mode generation are primarily caused by diameter changes [8]. Small-diameter couplers