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AN X-BAND WAVEGUIDE CELL FOR STUDY OF MICROWAVE PROPAGATION THROUGH MAGNETOPLASMA

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Abstract

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A metal X-band waveguide cell has been developed for studying microwave propagation through plasmas immersed in a longitudinal magnetic field. The cell consists of a length of circular waveguide mounted between turnstile junctions. Modification of these junctions permits the installation of discharge electrodes on the magnetic field axis. No glass cell is required. The discharge can be operated successfully at pressures in the range 0.25 to 1 Torr. Measurements of the changes in the amplitudes of the circular components of the wave polarization due to the presence of a magnetoplasma in the cell, allow the electron density and electron collision frequency to be calculated.

Author

Introduction

The use of glass discharge vessels for guided wave propagation of microwaves through a plasma has several disadvantages: construction and assembly are more difficult than with an all-metal system, and uncertainties in the appropriate boundary conditions are introduced by the presence of the glass. Where a longitudinal magnetic field is involved, it is also advantageous to have both discharge electrodes parallel to the axis of the vessel and to the direction of microwave propagation. This axial electrode symmetry minimizes wall effects, in contrast to discharge vessels used by other workers[1,2] in longitudinal magnetic fields. Figure 1 shows two types of glass discharge cell in which one or both electrodes are perpendicular to the axis of the cell. It has been found experimentally that with asymmetrical electrode construction the plasma may be displaced in the magnetic field to the extent of striking one of the walls of the glass vessel, even for magnetic fields as low as 600 gauss and discharge currents as low as two milliamps. This effect does not occur with symmetrical electrode design for fields as high as 6000 gauss. This situation is represented diagrammatically in Figures 2a and 2b. Discharge vessels ranging in length from 15 to 50 cm and in diameter from 1 to 5 cm have all shown this effect for pressures ranging from 2 Torr to 0.2 Torr.

Several other types of discharge vessel which could be incorporated in waveguide geometry were tried out in magnetic fields. The all-glass design of Fig. 3a, with extended glass tubing, did not prevent wall effects near the electrodes and is difficult to assemble. The hollow cathode discharge cell[3] of Fig. 3b is more convenient to mount in conjunction with waveguide

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1. V. E. Golant, et al, Sov. Phys. Tech. Phys. 6, 38, (1961).
2. L. Goldstein, et al, p. 121, "Electromagnetics and Fluid Dynamics of Gaseous Plasma," Polytechnic Press (Interscience), (1962).
3. K. C. Stotz, NASA TN D-226, (1963); E. H. Holt, K. C. Stotz, Rev. Sci. Inst. 34, 1285, (1963).

components but also suffers from wall effects which extinguish the discharge in magnetic fields.

A satisfactory design was achieved using symmetrical axial electrodes in a cylindrical metal cell which was coated with an insulating layer of glyptal. Microwave propagation through the cell was made possible by incorporating at each end a modified turnstile junction[4,5] consisting of four X-band waveguide ports and a coaxial metal stub assembly. The inner insulated metal rod of the coaxial stub functions both as part of the microwave matching unit and as a discharge electrode. Pressure windows vacuum seal the waveguide. The size of the circular guide restricts propagation to the TE_{11} mode but permits both senses of circular polarization. The change in circular components of the polarization due to the magnetoplasma allows electron density and collision frequency to be determined directly. A variety of experiments are therefore possible with the cell: for example, a study of diffusion decay of a plasma in a magnetic field[6], or of microwave propagation in the direction of the magnetic field through a magnetoplasma.[7]

Microwave Design

In the cell the modified turnstile junction is used as a six-port device in which circular and rectangular ports are matched simultaneously by the adjustment of two coaxial cylindrical metal stubs A and B, shown in Fig. 4. When correctly matched the theoretical power distribution between the various ports for different input modes is shown in Tables 1 and 2.

In the actual cell, see Fig. 5, it is possible to launch any polarization

4. R. S. Potter, NRL Rep. 4670, (1955).
5. P. J. Allen, R. D. Tompkins, Proc. IRE 47, 1231, (1959).
6. V. E. Golant, A. P. Zhilinskii, Sov. Phys. Tech. Phys. 5, 699, (1961).
7. D. W. Mahaffey, Phys. Rev. 129, 1481, (1963).

down the circular guide by appropriate input conditions. If a linearly polarized wave is fed in port 1 with matched terminations on the other three ports, a linearly polarized wave will be propagated. With adjustable short circuits on arms 2 and 4, it is possible to generate circular or elliptic polarizations. If the turnstile junctions are correctly matched, there will be no losses of power by reflection or through the coaxial transmission line of the matching stubs.

The approximate dimensions of the coaxial stub assembly to be used as the matching unit were easily estimated.[4,5] However, the actual construction involved a compromise between the microwave design, the requirements for suitable vacuum sealing, and for discharge electrodes which would operate satisfactorily. The waveguide window assemblies were brazed to a short brass cylinder of 2" inner diameter and 1/4" wall thickness. A 3" transition taper section was then brazed between the waveguide ports and the cylindrical waveguide of inner diameter 2.06 cm. An overall length of 46.5 cm between the waveguide ports at opposite ends was chosen to suit the available magnetic field coils. The air-core solenoid magnet used had an internal diameter of 12", so that assembly of the waveguide cell presented no problem. However, preliminary tests were carried out in another solenoid magnet with an internal diameter of only 6". For this reason a maximum overall diameter of 5" was chosen for the cell ends with waveguide pressure windows attached.

Vacuum and Discharge Considerations

Ultek curvac flanges were used to vacuum seal the open end of the 2" diameter brass cylinder. The whole matching unit was constructed as an integral part of one of the vacuum flanges so that it could be easily removed, adjusted, or replaced. The electrode stubs were of tungsten and the insulation used was teflon. However, as shown in Fig. 6, a ceramic tip was added to the end of the teflon where local heating from the discharge would otherwise cause deterioration of the insulating material.

A more satisfactory vacuum vessel could be obtained by using stainless steel throughout, rather than brass, and by the use of ceramic insulation which could be soldered directly to the metal. Another improvement would be the use of teflon insulation on the interior walls of the discharge vessel instead of glyptal. However, tests have shown that the electrical insulation of glyptal withstands baking at temperatures of 600^{o}F, so that a low temperature bakeout of the vacuum system is possible.

A prototype metal cell with 1/4" holes along the guide, sealed by waxed-in glass windows, has been used to make visual observations of the discharge. A glass cell with identical electrode structure and similar geometry was also used. A discharge can be successfully operated at pressures from 0.25 to 1 Torr and currents of 5 milliamps. The discharge is quite stable and fills the whole vessel uniformly. However, if one electrode and the metal walls are both at ground potential the discharge becomes unstable and the plasma near the electrodes tends to be displaced towards the adjacent walls in spite of the layer of glyptal insulation. With a "floating" DC supply or, for pulsed operation, an isolating transformer, the discharge is quite stable.

When a magnetic field is applied the discharge constricts and for a field of 1000 gauss is restricted to the central region with a radius of approximately 1 cm.

Matching Considerations

Adjustment of the matching units at both ends was made to give a constant frequency response over as broad a range as possible. This is necessary because the change in dielectric constant of the plasma in a magnetic field alters the effective wavelength of the propagated microwave signal. An X-band sweep oscillator was used to deliver power to the cell and to generate the oscilloscope sweep display of the response of the crystal detectors mounted on the output ports. The dimensions of the components of the matching units when correctly adjusted are shown in Fig. 6 and the frequency response of the cell in Fig. 7. Within the range 9.4 to 9.8 Gc/s the transmitted signal is constant to within 0.5 db, but drops off outside this range.

The reflected power level is more than 30 db below the incident power level. The amount of cross-coupling between adjacent arms represents a power level of $<$ 25 db. This should be zero but perfect symmetry of the junctions would be required to achieve this.

Analysis of Microwave Output Signals

The signals from the four waveguide output ports provide information about the change in polarization of the propagated EM wave due to the magnetoplasma. The polarization parameters are defined in the following way:

Let the orthogonal components of the electric field be represented by

$$E_1 = A_1 \cos(-\omega t)$$

$$E_2 = A_2 \cos(\phi - \omega t)$$

where A_1 and A_2 are the amplitudes of the components,

ω = the angular frequency

ϕ = the phase difference

The amplitude ratio A_2/A_1 may be written as

$$A_2/A_1 = \tan \theta/2, \qquad 0 < \theta < \pi,$$

and the right and left circular components can be expressed[8,9] as

$$C_+ = \left[\cos \theta/2 + \sin (\theta/2) \sin \phi - i \sin (\theta/2) \cos \phi\right]/2$$

$$C_- = \left[\cos \theta/2 - \sin (\theta/2) \sin \phi + i \sin (\theta/2) \cos \phi\right]/2$$

The response of crystals mounted on ports 1 and 2 at the output end can be used to obtain θ. The outputs of ports 3 and 4 are combined at a hybrid junction and the difference in electrical length between port 3 and the hybrid junction and port 4 and the hybrid junction is adjusted by means of a phase shifter to be a multiple of $\pi/2$. It can be shown[8] that the magnitudes of the signals from crystals mounted on the H and E arms of the hybrid junction are the same as the magnitudes of the right and left circular components of the wave. Thus the second polarization parameter ϕ can be determined.

If the amplitudes of the circular wave components entering and leaving the magnetoplasma are C_+ and C_- and C_+' and C_-' respectively, then

$$C_+'/C_-' = e^{-(k_+ - k_-)L} C_+/C_-$$

where $k_\pm$ = the propagation constant of the appropriate circular component

$= \beta_\pm + i\,\alpha_\pm$

where $\beta_\pm$ = the phase shift per unit length

$\alpha_\pm$ = the attenuation per unit length

L = the length of the magnetoplasma in the direction of propagation.

It is possible to evaluate the phase shift and attenuation parameters separately.

8. R. E. Haskell, Rensselaer Polytechnic Institute, Plasma Research Laboratory, TR 8, (1963).

9. K. C. Westfold, J. Opt. Soc. Am., 49, 717, (1959).

Values of the relative output signals at 9.5 Gc/s in arms 1 and 2 for a discharge current of 4 milliamps are shown in Fig. 8 for various values of magnetic field. These show the sensitivity of the technique since quite large signals are obtained.

Relation to Plasma Parameters

The rotation of the plane of polarization per unit length is given by

$$\psi = (\beta_+ - \beta_-)/2$$

When the electron collision frequency ν is very much less than the microwave angular frequency ω, ψ can be used to determine the average electron density $\bar{n}_e$ directly. It is necessary to know the radius of the region containing the plasma relative to the radius of the guide, so that visual inspection of the plasma column in the magnetic field is required.

When ω is close to the cyclotron frequency, ψ will be dependent on both n_e and ν. The collision frequency ν may be calculated from the attenuation factor.

TABLE I Power distribution between the various ports when microwave power enters through one of the rectangular arms.

Port	1	2	3	4	5	6
Power Level	P	P/4	0	P/4	P/2	0

TABLE II Power distribution between the various ports when microwave power enters through the circular guide.

Port	1	2	3	4	5	6
Power Level	P/2	0	P/2	0	P	0

TABLE III End Matching Conditions for Turnstile Junctions

End	A	B	C	D
1	2 1/2"	9/32"	3/16"	1/32"
2	1 3/16"	1/4"	1/16"	1/2"

Captions for Figures

Figure 1 Glass discharge vessels with off-axis electrodes A and C.

Figure 2 (a) Plasma between off-axis electrodes A and C displaced in an external magnetic field towards vessel walls.

(b) Plasma between axially symmetric electrodes A and C is not in contact with vessel walls in an external magnetic field.

Figure 3 (a) Glass cell with extended glass tubing to restrict the plasma to the central region of the vessel.

(b) X-band waveguide hollow-cathode discharge cell.

Figure 4 Turnstile junction comprising four rectangular waveguide ports, one circular port, and one coaxial port.

Figure 5 Schematic diagram of the waveguide cell showing the modified turnstile junctions at each end of a length of circular guide.

Figure 6 Schematic diagram of the coaxial metal stub assembly used for microwave matching and in which the inner rod acts as a discharge electrode. For dimensions see Table 3.

Figure 7 Transmission characteristics of the cell as a function of frequency.

Figure 8 Signal levels of the two orthogonal output arms for a linearly polarized 9.5 Gc/s input signal passing through the magnetoplasma, as a function of magnetic field.

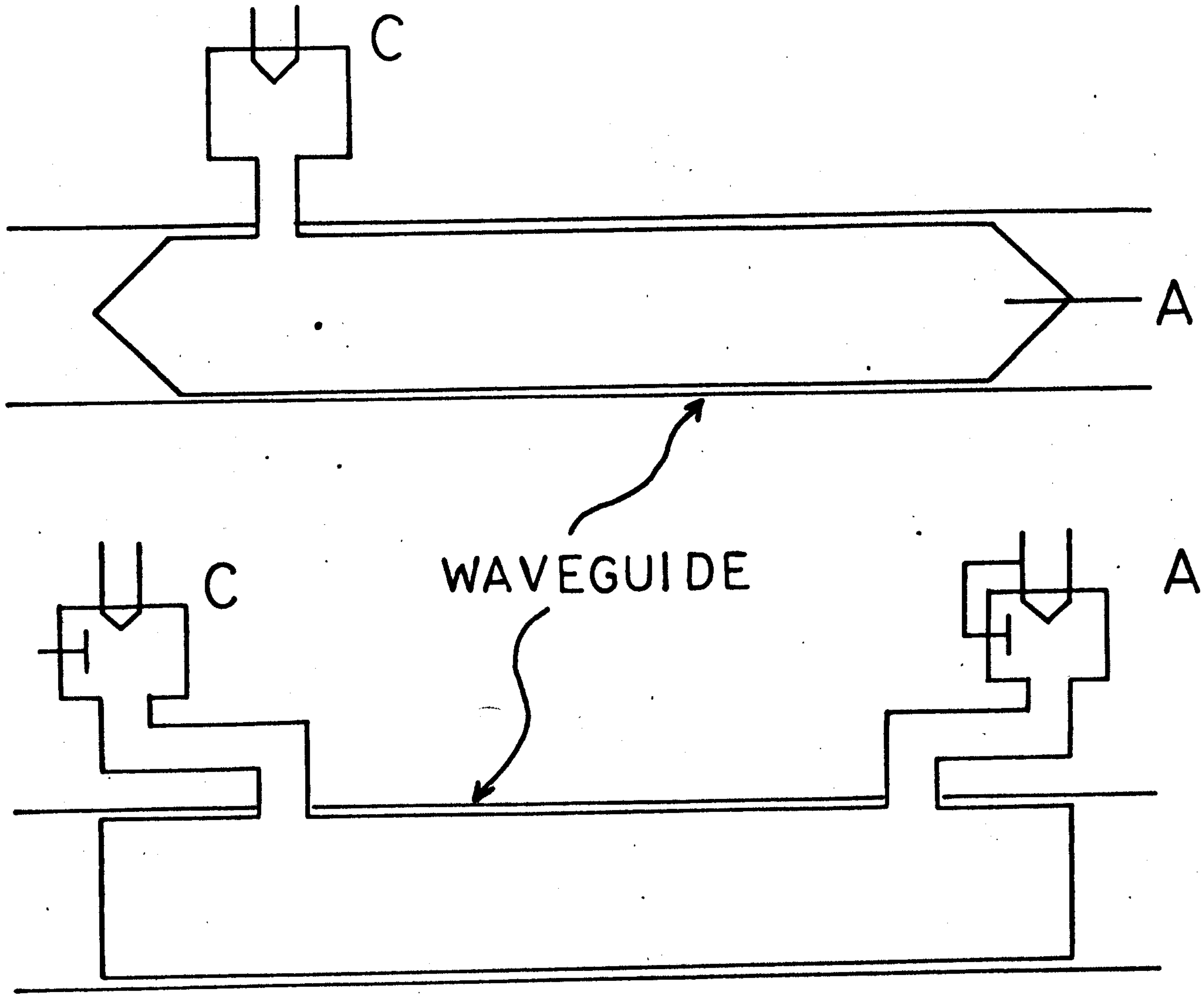

Fig. 1 Glass Discharge Vessels with Off-Axis Electrodes A and C

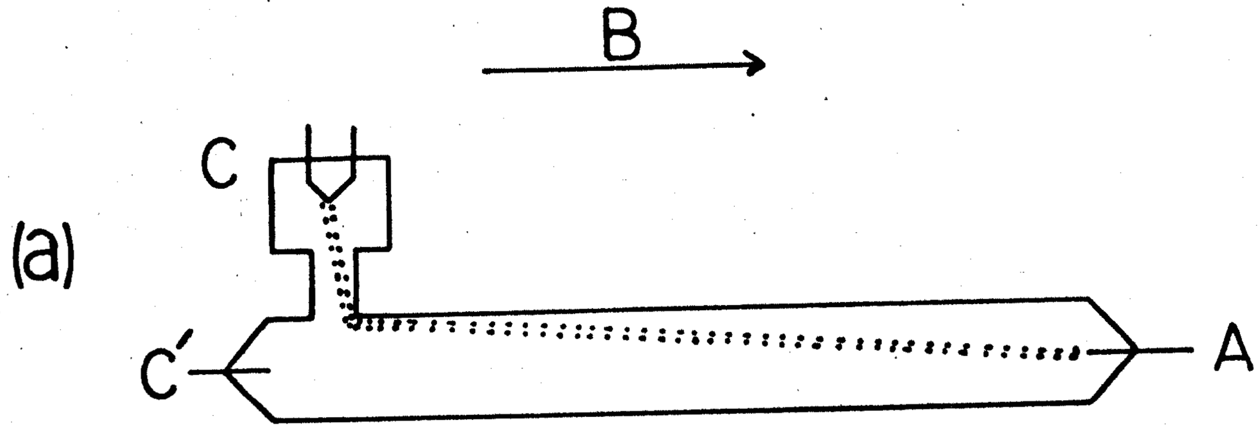

Fig. 2 (a) Plasma between Off-Axis Electrodes A and C

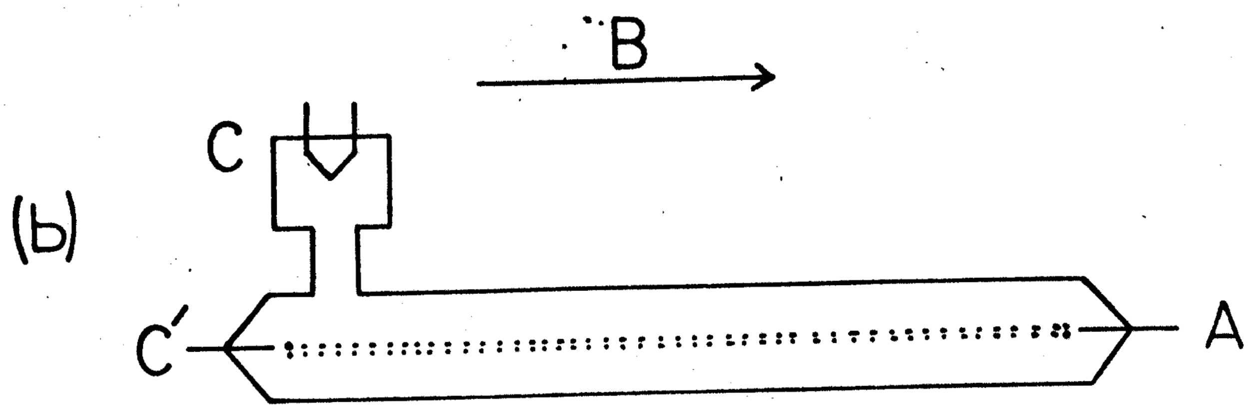

Fig. 2 (b) Plasma between Axially Symmetric Electrodes A and C'

(a)

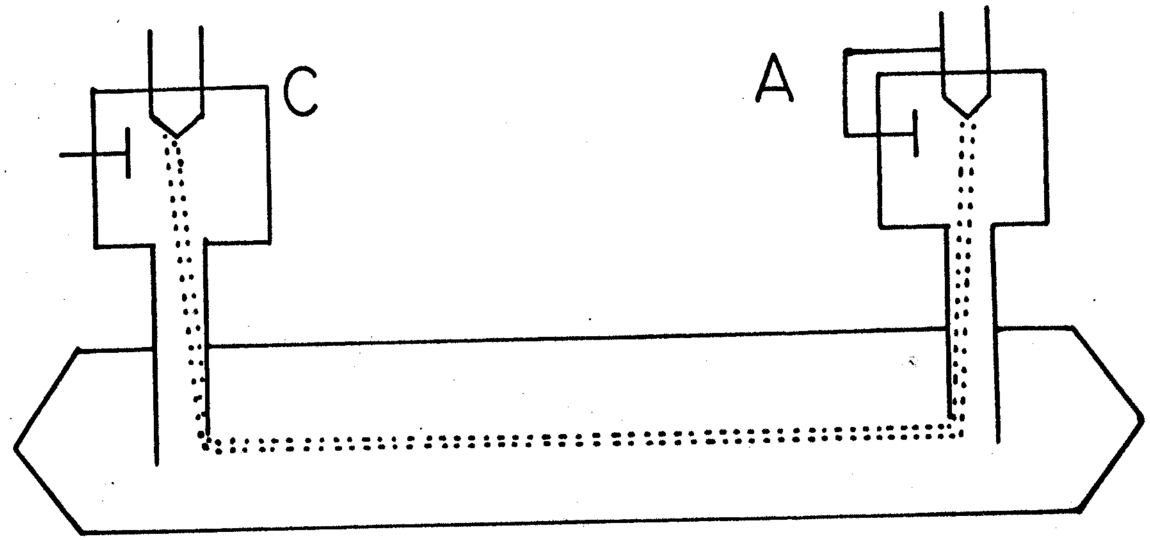

Fig. 3 (a) Glass Cell with Extended Glass Tubing

(b)

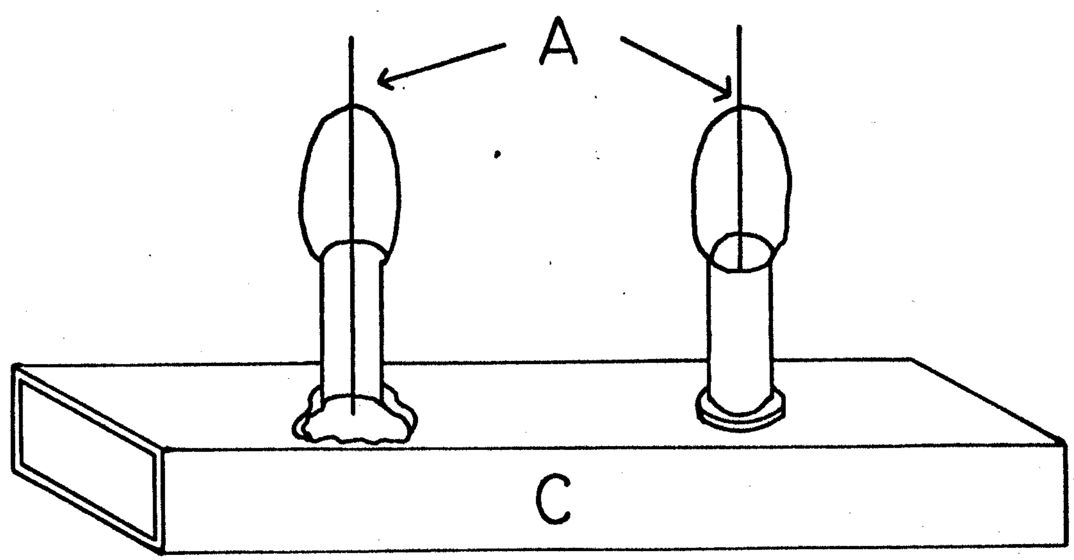

Fig. 3 (b) X-Band Waveguide Hollow-Cathode Discharge Cell

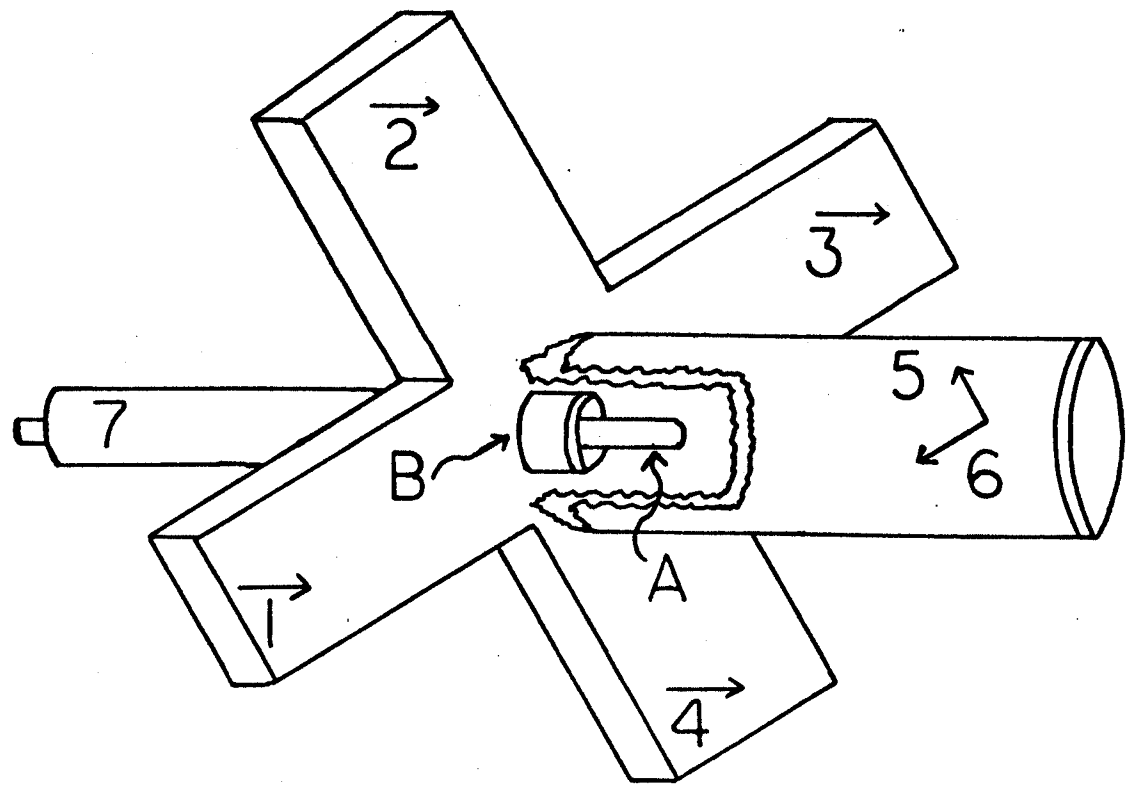

Fig. 4 Turnstile Junction

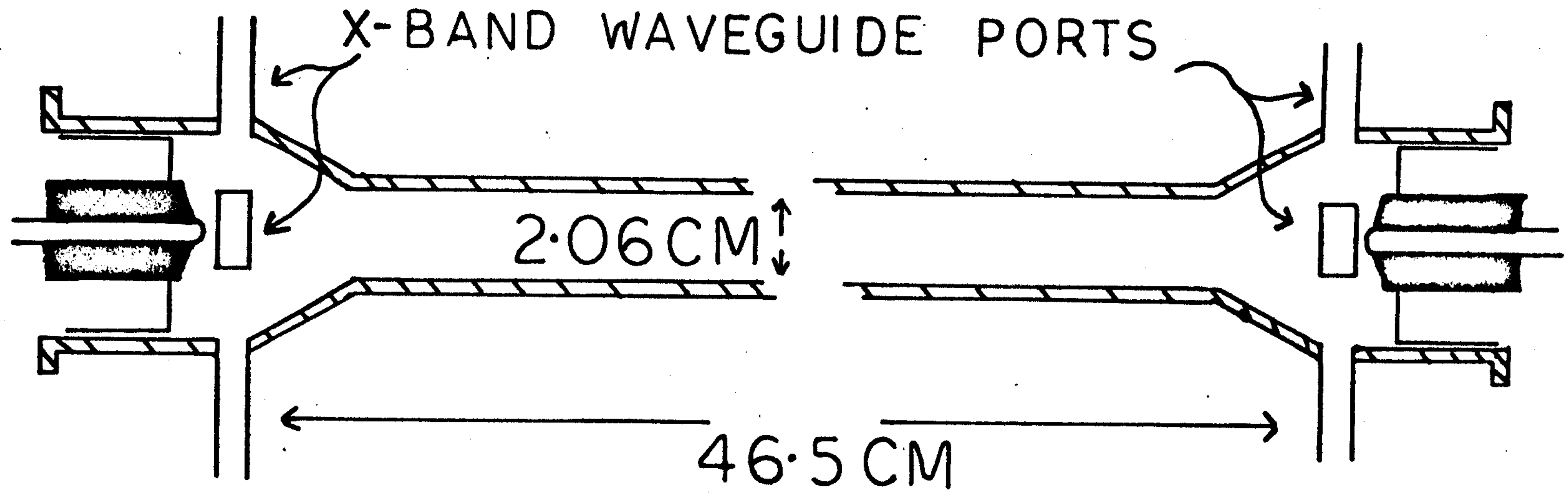

Fig. 5 Schematic Diagram of the Waveguide Cell

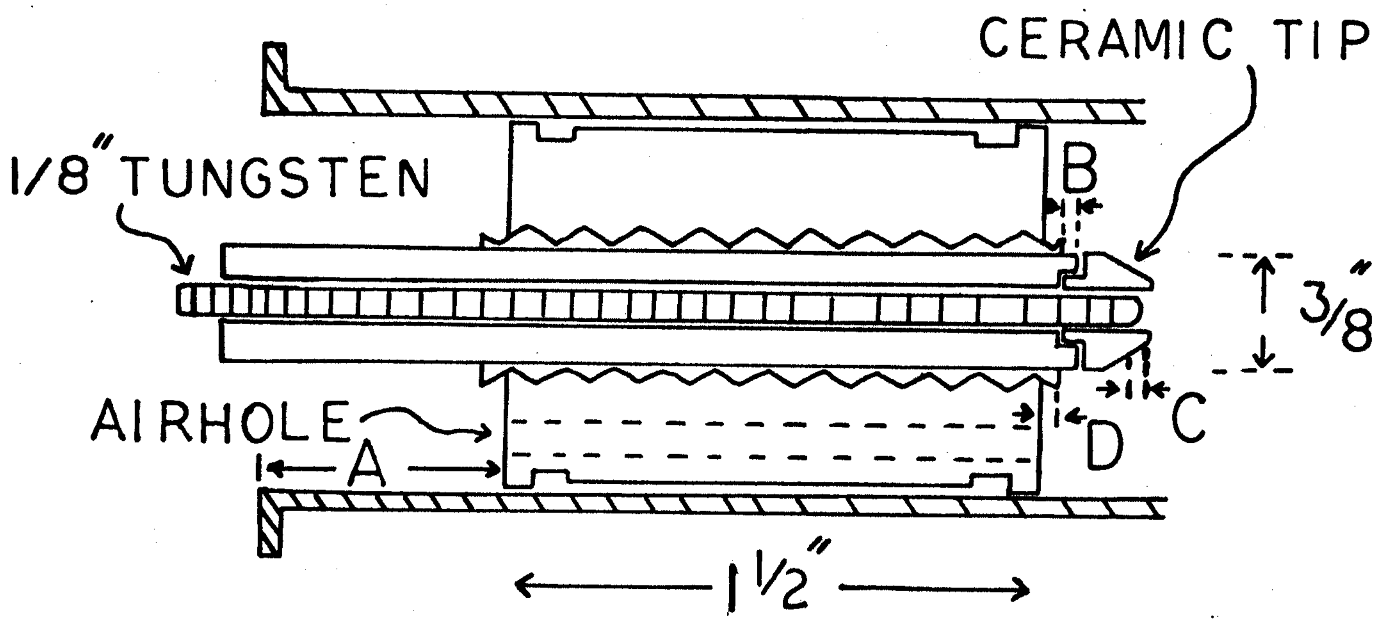

Fig. 6 Schematic Diagram of the Coaxial Metal Stub Assembly

(For dimensions see Table 3.)

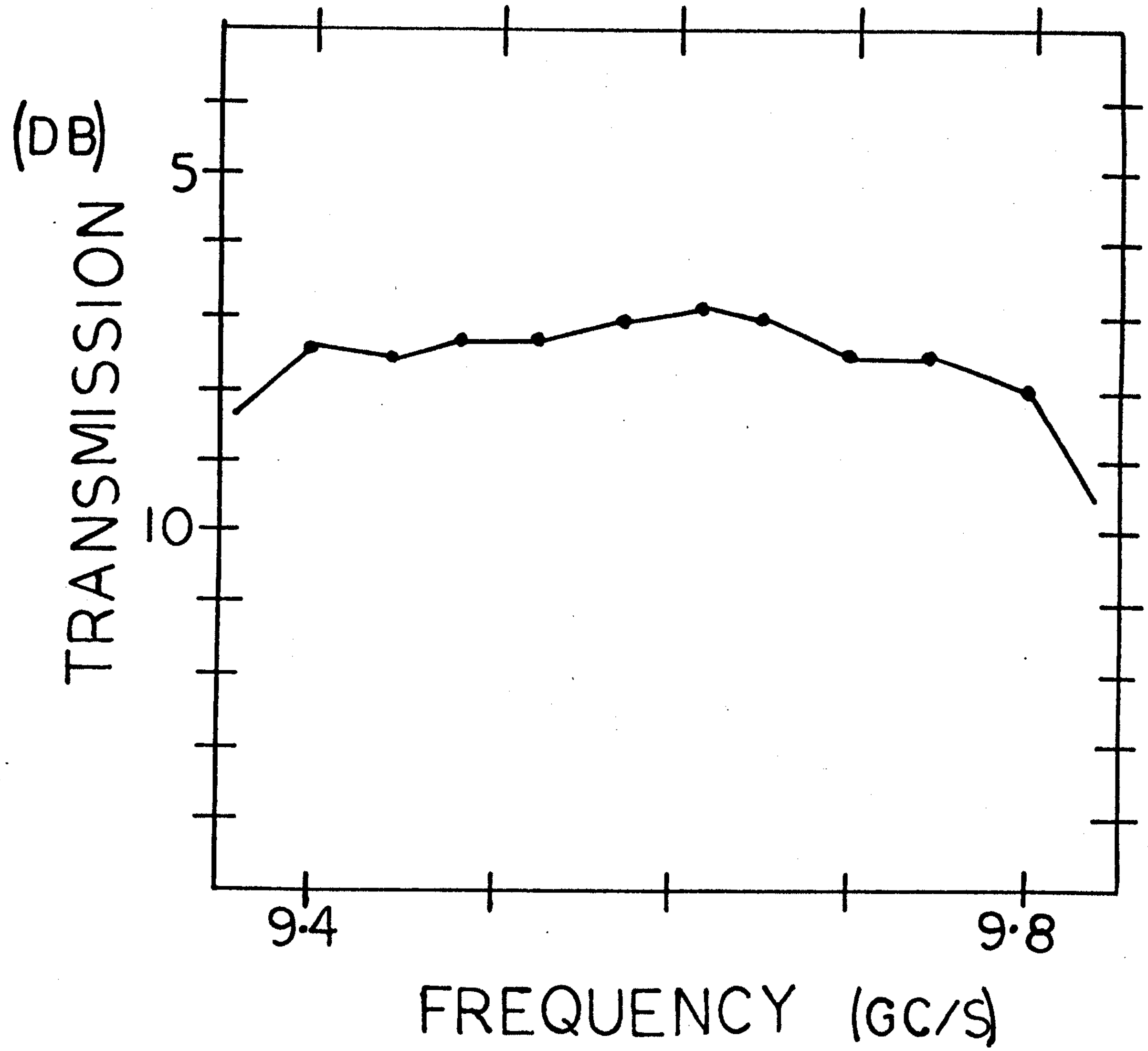

Fig. 7 Transmission Characteristics of the Cell

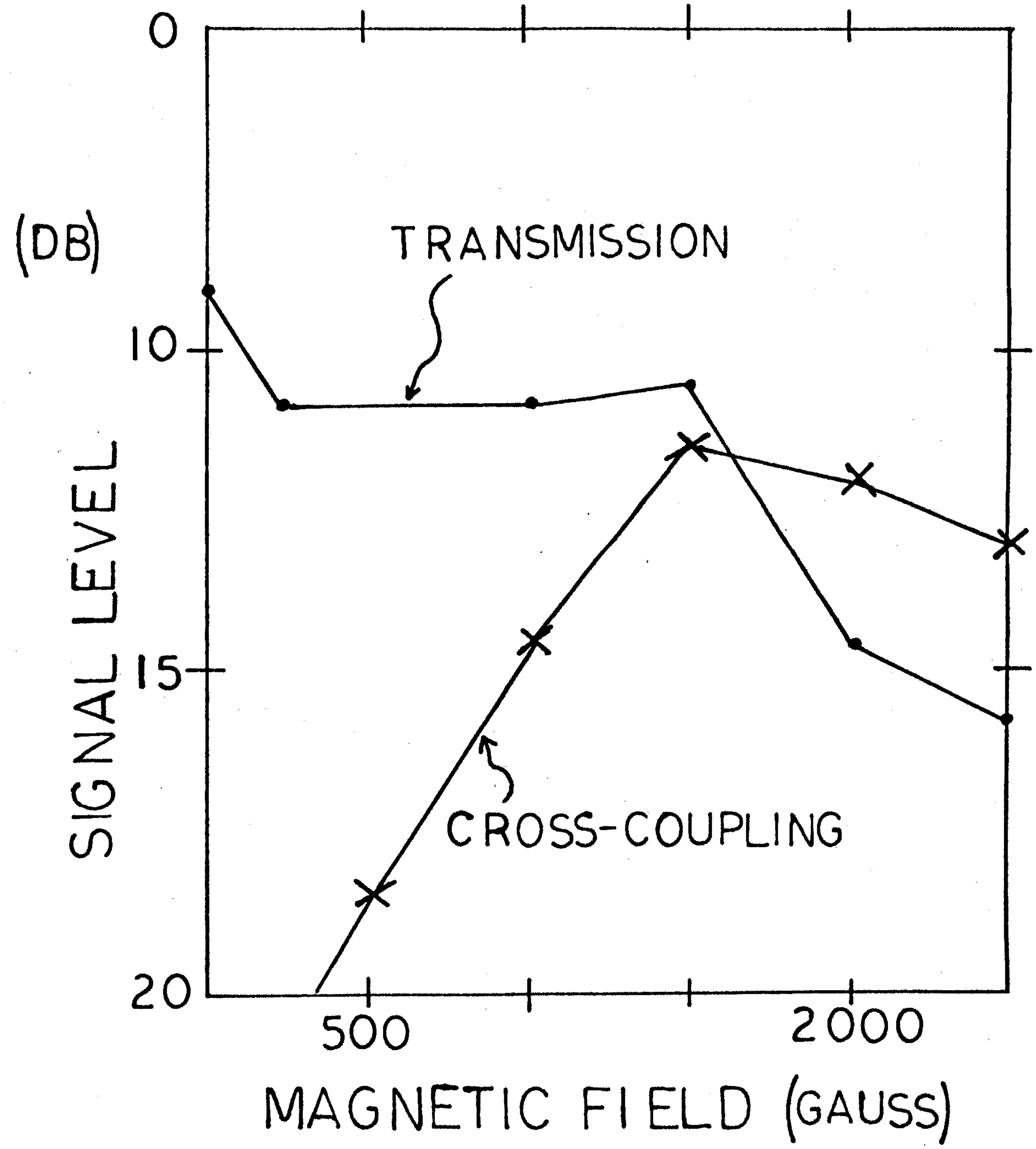

Fig. 8 Signal Levels of the Two Orthogonal Output Arms as a Function of Magnetic Field