BREAKTHROUGH IN CORRUGATED CONICAL HORN RESEARCH IN QUEEN MARY COLLEGE. UNIVERSITY OF LONDON DURING LATE 1960'S

A REMINISCENCE BY PRADIP KUMAR SAHA

Search for Low-Noise Feed Horns: Situation in 1960s

Desired Characteristics:

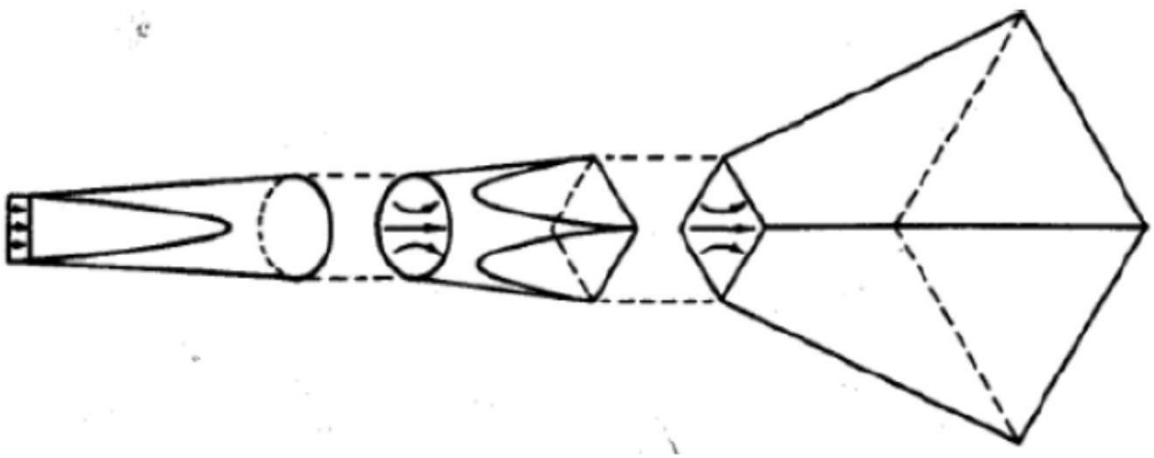
- ❖ **High Efficiency**
- ❖ **Co-polar Pattern Symmetry**
- ❖ **Low (-30 dB or better) sidelobes**

Among various structures invented, perhaps the most notable, most ingenious were:

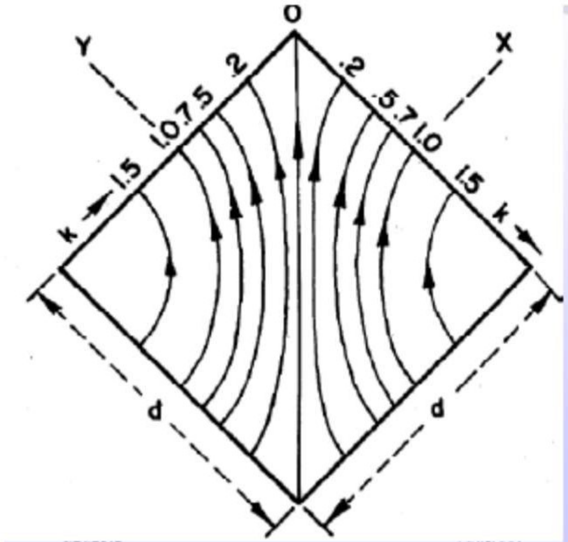
(1)DiagonalHorn(1962)–a shaped-aperture horn

(2)PotterHorn(1963)–a dual-mode conical horn.

Diagonal Horn



Rectangular waveguide to diagonally polarized horn – Mode transducer

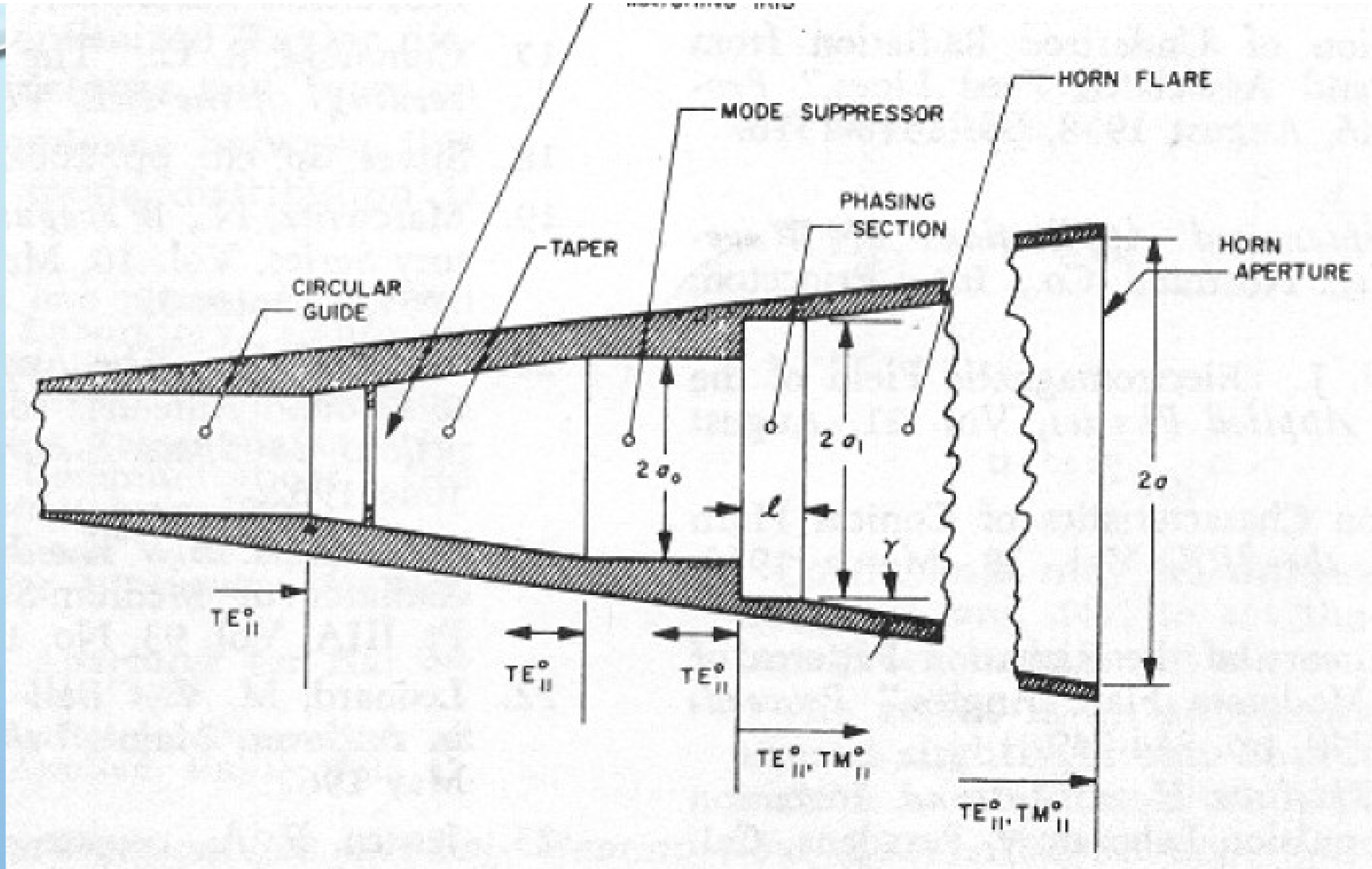


The field pattern in the aperture

Diagonal Horn

It is a small-flare shaped-aperture (square-aperture) pure-mode horn that is diagonally polarized.

- **The co-polar pattern is almost circularly symmetric, but**
- **the peak cross-polar level is as high as -16 dB in the $\pm$ 45^{o} planes.**
- **The sidelobes in the principal planes are about -20 dB.**



Dual-mode Potter Horn

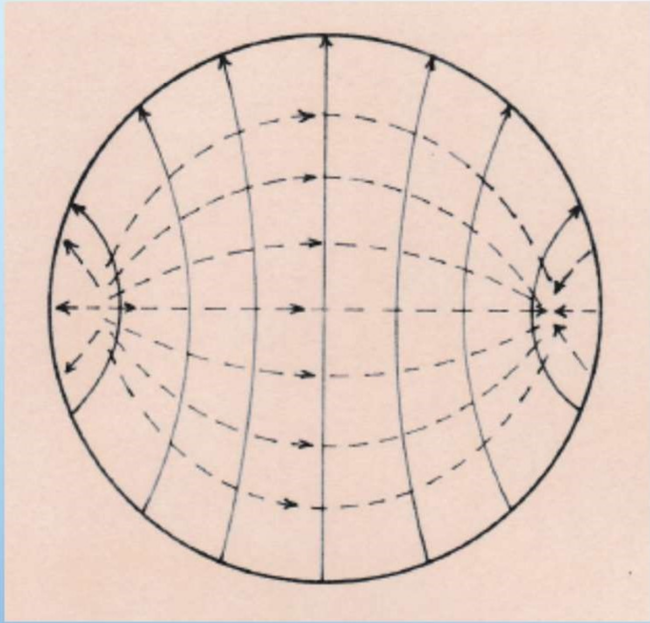
Potter Horn

Potter horn used both circular TE_{11} and TM_{11} modes in proper amplitude ratio to achieve

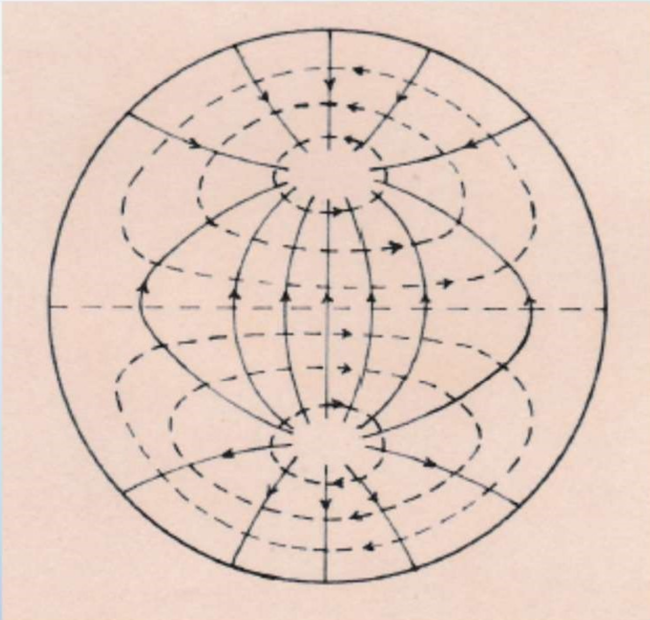
- ❖ **aperture distribution tapered to zero in all planes,**
- ❖ **complete beam-width equalization in all planes,**
- ❖ **complete phase-centre coincidence in all planes,**
- ❖ **at least -30 dB sidelobe level in E-plane.**
- ❖ **H-plane performance remains unchanged.**

Disadvantages:

- ❖ **Narrowband**
- ❖ **Since TM_{11} does not radiate axially, Potter horn has lower gain than a TE_{11} horn of same aperture size.**
- ❖ **Elaborate design procedure.**



TE_{11}



TM_{11}

Wide-Flare Conical Horn: A. F. Kay (1962)

- ❖ Such horns are characterized by Δ (the maximum phase deviation of spherical phase front from aperture plane) > $\lambda/2$, unlike "diffraction limited" horns with $\Delta<\lambda/2$.
- ❖ Phase centres are at the throat of the horn.
- ❖ Patterns have virtually no sidelobes.
- ❖ Beamwidth, to first approximation, is independent of λ.
- ❖ At $\theta=\theta_0$ (Half Flare Angle), E-plane pattern level is 6-9 dB depending on θ_0 and independent of λ; in H-plane it is 13-25 dB depending on θ_0 and slightly on Flare Length/λ ratio.
- ❖ Heavy E-plane edge illumination spoils phase-centre coincidence and lowers secondary aperture efficiency.

Phase Centre Location in Feedhorn

When a feed with widely separated E-plane and H-plane phase centres illuminates a reflector, there is inevitable axial de-focusing. This -

- **reduces the antenna gain,**
- **raises the side-lobe level in a symmetrical way,**
- **and, most importantly in some applications, raises the peak level of cross-polarization in the 45^{o} plane.**

Wide-Flare Corrugated Conical Horn: A. F. Kay (1964)

- If the inner wall of wide-flare conical horn was corrugated with transverse grooves that present capacitive series reactance to the incident field in the E-plane, radiation patterns are almost symmetrical over a broad frequency band.
- This indicated that the boundary conditions for the radially flowing field are the same in every axial plane independent of polarization.
- This was explained from an analogy with plane corrugated surface.

- **If a plane wave, traveling transverse to the grooves on a plane corrugated surface, is incident at an angle ψ to the perpendicular to the surface, the reflection coefficients for TE/TM waves are given by**

$$R_{TE} = -1$$

$$R_{TM} = \frac{\cos\psi + jX}{\cos\psi - jX}$$

where X is the surface reactance.

- **In the limit $\psi \rightarrow 90^o$, $R_{TE} = R_{TM} \rightarrow -1$. Implication: on the corrugated surface, tangential components of both E and H vanish.**
- **This can be true for both inductive (X>0) and capacitive(X<0) surfaces.**
- **Inductive surface is inappropriate for antenna applications as it supports surface waves which do not vanish on the surface. Only capacitive surface is desirable.**
- **Thus, a boundary condition which is independent of polarization, produces a field that is independent of polarization. Accordingly, such a feed was named – SCALAR FEED.**

Scalar Feed
Half Flare Angle - 70^o

A. F. Kay (1964)

Hybrid Mode Waveguide Feed: Minnett and Thomas (1966)

- Study of the focal field of a circularly symmetric parabolic reflector, illuminated by a linearly polarized plane wave, together with the concept of symmetric radiation field led to the development of hybrid mode waveguide feeds.

- The scattered field at the focal plane of the reflector is a superposition of axially propagating hybrid waves that were identified with the fast hybrid modes of unit azimuthal dependence in a transversely corrugated circular waveguide.

- **It was shown that a waveguide to support the focal-field hybrid waves, its boundary must satisfy $X_z . X_\xi = - \eta_0^2$, where X_z is longitudinal surface reactance and X_ξ is circumferential surface reactance, η_0 is free-space wave impedance.**

- **Transversely corrugated surface with appropriate groove depth and sufficient number of corrugations per wavelength, approximately satisfies this condition with $X_z = \infty$ and $X_\xi = 0$.**

- **The condition can also be satisfied by longitudinally grooved surface with $X_z = 0$ and $X_\xi = \infty$. However, with such boundary, the waveguide would support pure TM_{1n} modes and hence would be unsuitable.**

In this backdrop,
P.J.B.Clarricoats and his research student Pradip Kumar Saha entered the fray in 1968.

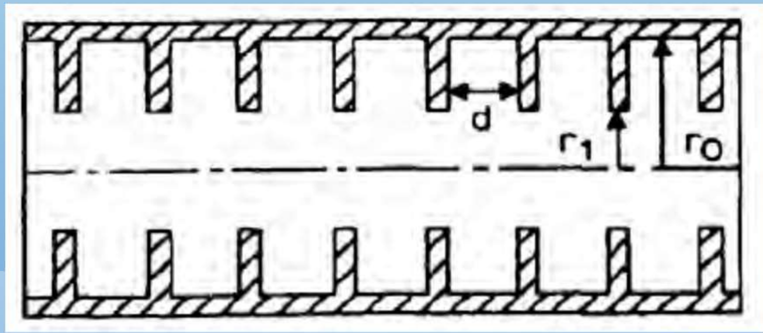
Aim: Study of Propagation and Radiation Characteristics of Fast Waves in Corrugated Circular Waveguides and Corrugated Conical Horns

Study of Fast Wave Propagation in Transversely Corrugated Circular Waveguide

- **Characteristic Equation**
- **Circularly Symmetric Modes**
- **Azimuthally Dependent Hybrid Modes**
- **Dispersion Diagrams**
- **Balanced Hybrid Condition**

Lowest Hybrid Mode HE_{11}

- **Field Pattern**
- **Power Flow**
- ***Attenuation***



Slot Depth $g=r_0-r_1$, Slot Width= d

Balanced Hybrid Condition

Perfect pattern symmetry and zero cross-polarization occur at the design frequency under **"Balanced Hybrid"** condition (BHC), when the corrugation depth is about one quarter of the wavelength.

For large apertures (large waveguide radii), slot depth g (for BHC) ≈ $\lambda/4$. For small apertures $g>0.25\lambda$, being ≈ 0.3λ for 2λ aperture.

Example: For a 10 GHz horn with aperture diameter of 3λ, slot depth of 0.3λ, peak cross-polar level in 45^o plane is –47 dB.

Dimensionless Hybrid Factor $\bar{\Lambda}$

$$\bar{\Lambda} = j\eta_0 \frac{H_z}{E_z} = -m \frac{(\beta_{mn}/k_0)}{F_m(k_{cmn}/r_1)}$$

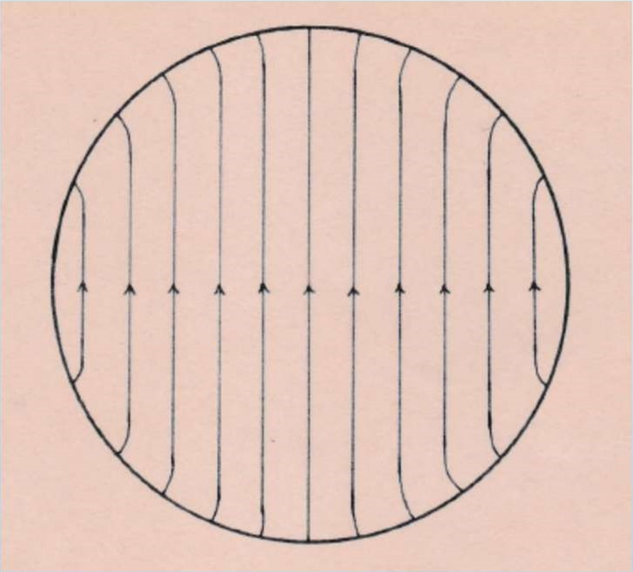
$$F_m(x) = x \frac{J_m^{/}(x)}{J_m(x)}$$

$$\bar{\Lambda} = 0 \quad for\ \ TM\ modes\ ; \quad 1/\bar{\Lambda} = 0 \quad for\ \ TE\ modes$$

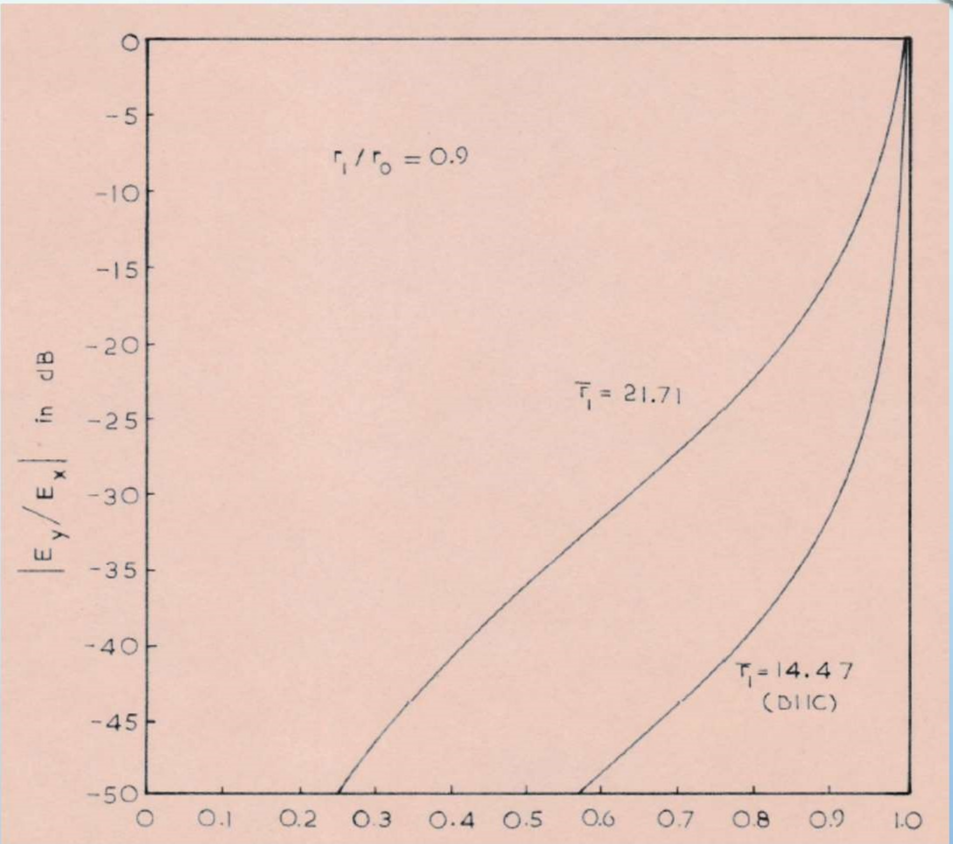
$$= \pm 1\ \ for\ hybrid\ modes\ under\ BHC$$

Upper sign for HE_{mn} modes
Lower sign for EH_{mn} modes

Fields in Corrugated Waveguide



Transverse E Field of Balanced HE_{11} Mode

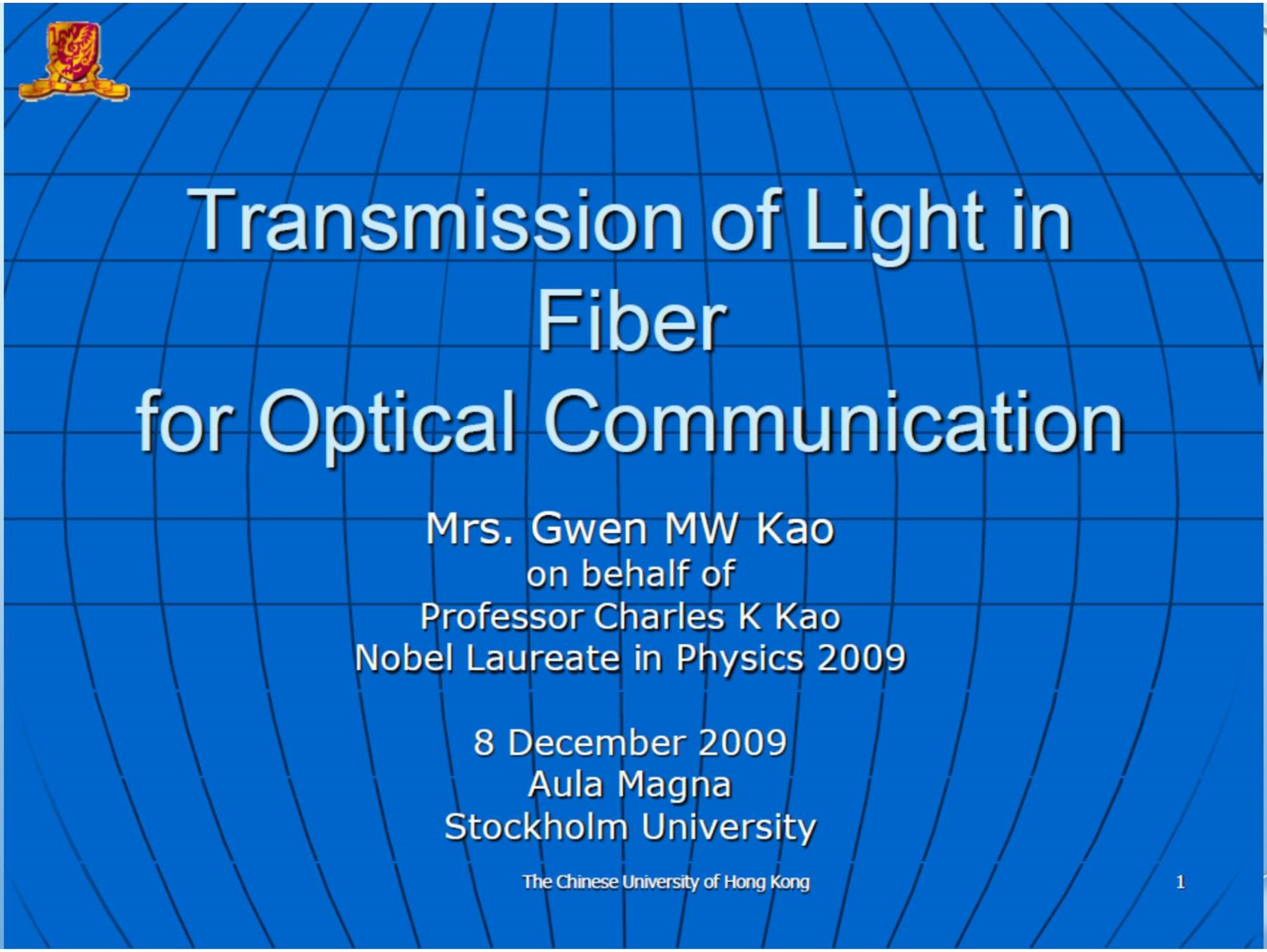


r/r_1

Cross-polar Component of HE_{11} Mode in 45^o Plane

Attenuation in Corrugated Circular Waveguide

The Theoretical attenuation of HE_{11} mode under balanced hybrid condition and over a band around the frequency corresponding to BHC can be lower than the attenuation in a TE_{11} circular waveguide of same diameter $2r_1$.


Transmission of Light in Fiber
for Optical Communication
Mrs. Gwen MW Kao
on behalf of
Professor Charles K Kao
Nobel Laureate in Physics 2009
8 December 2009
Aula Magna
Stockholm University
The Chinese University of Hong Kong
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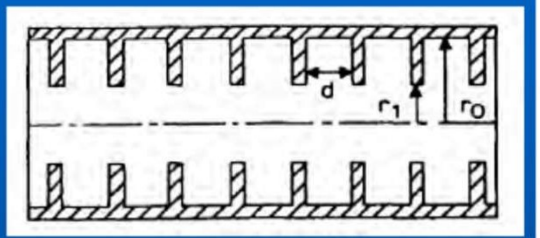
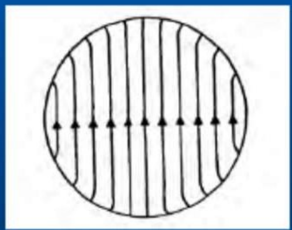
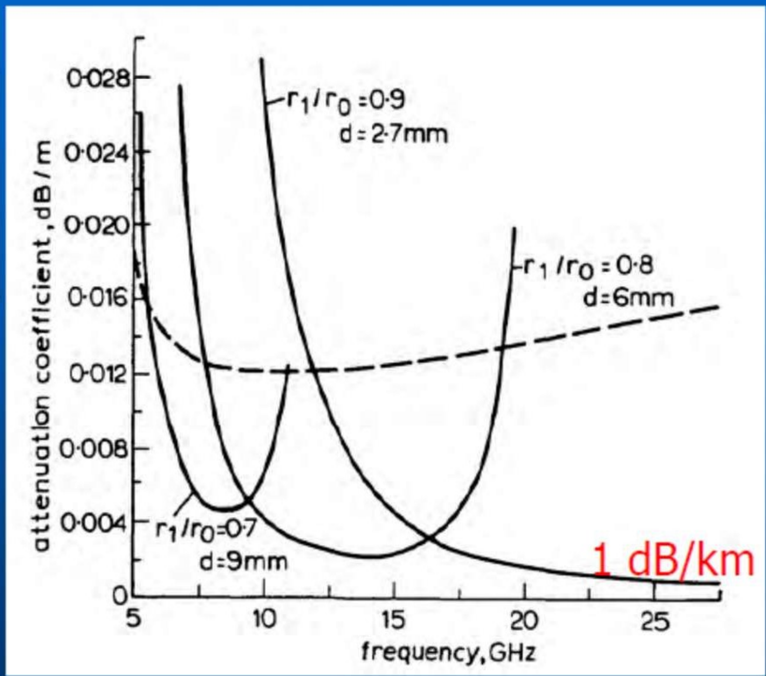
Low-loss corrugated circular waveguide





HE11 Mode

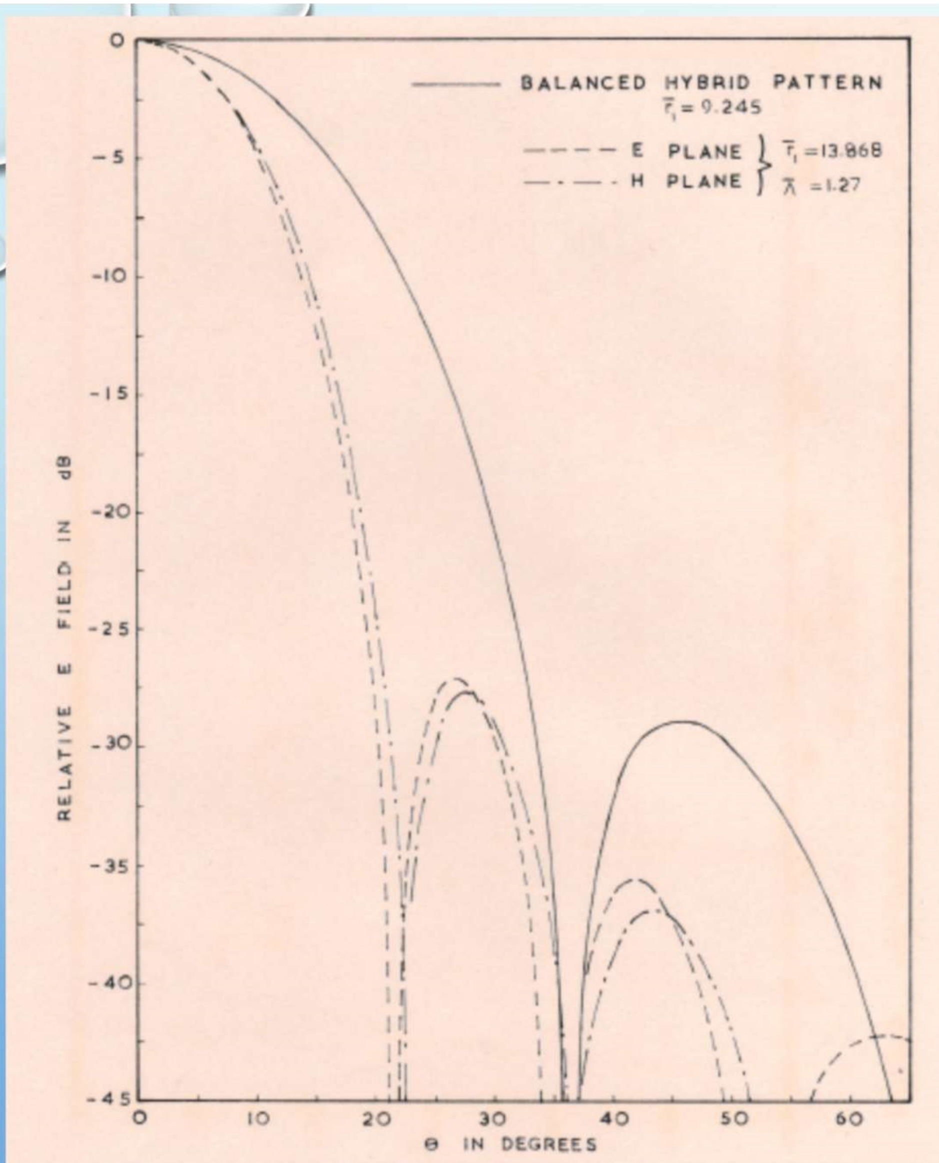


P.J.B. Clarricoat & P.K. Saha, "Attenuation in Corrugated Circular Waveguide," *Elect. Lett.*, Vol.**12**, pp.370-2, 1970.

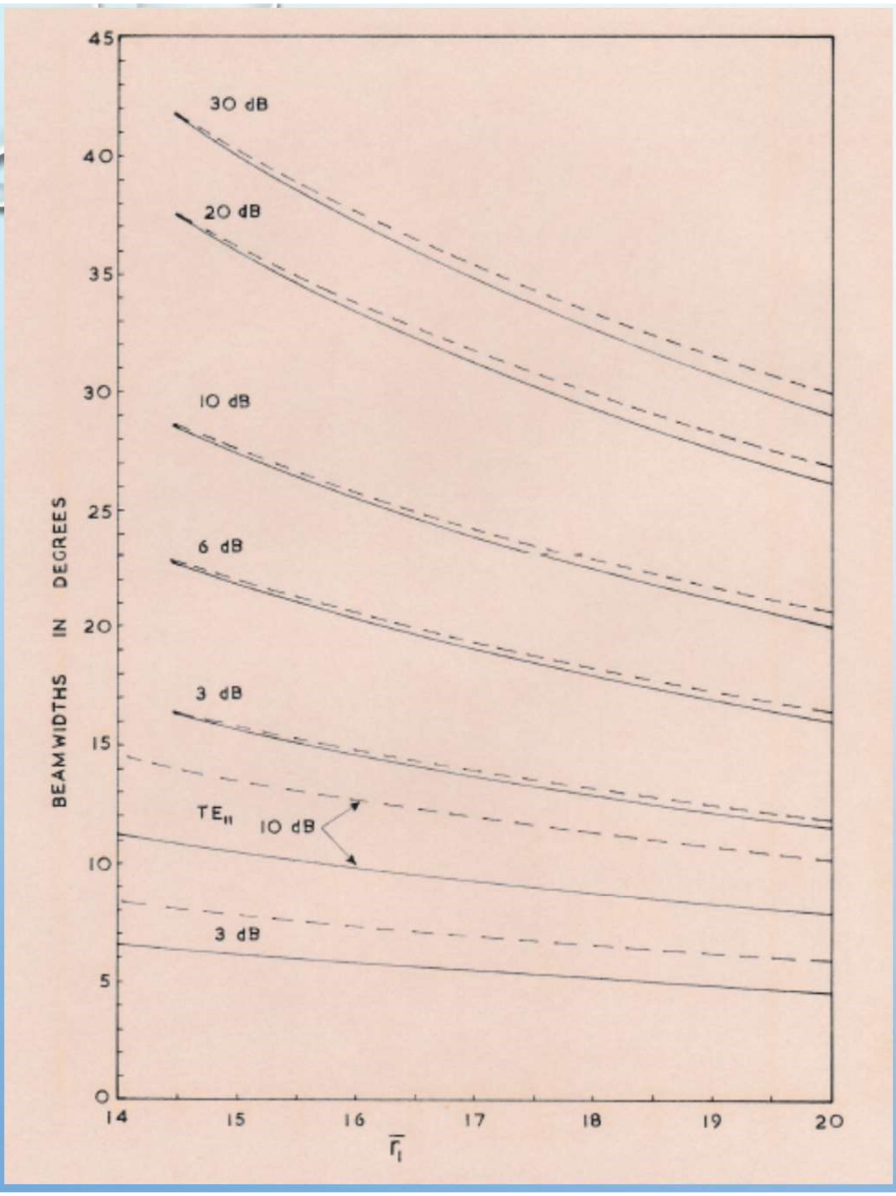
$\lambda/d \approx 5$ at BHC ; ≈ 3 at 1.5 * B H frequency

Radiation From Corrugated Circular Waveguide

- Far-field Pattern by Kirchhoff-Huygen Integration
- Hybrid Mode Radiation Fields
- HE_{11} Mode Radiation Patterns
- Performance of Parabolic Reflector with Corrugated Waveguide Feed
- An Experimental Narrow-Flare (12^o half flare) Corrugated Horn
- Measured Patterns and Input VSWR: 8.5 – 11.0 GHz

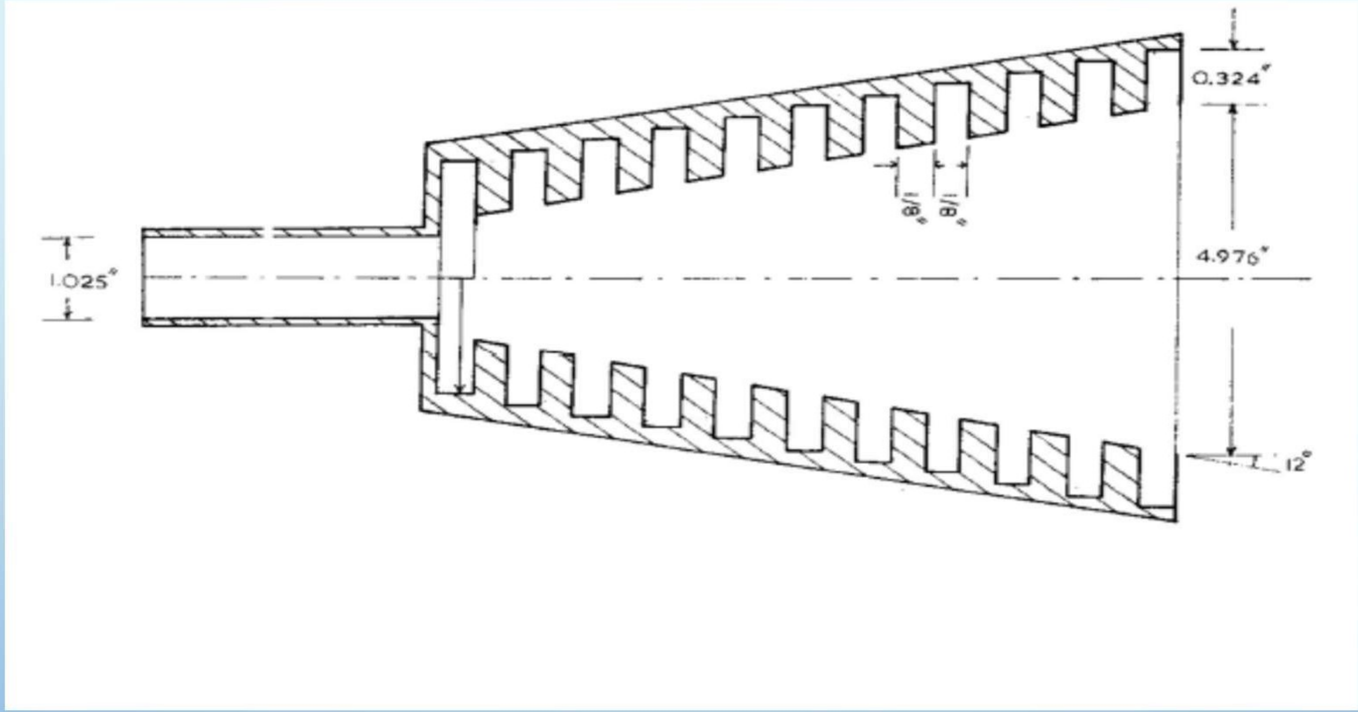


Theoretical Radiation Patterns of HE_{11} Mode in Corrugated Circular Waveguide under BHC and at 1.5 times higher frequency



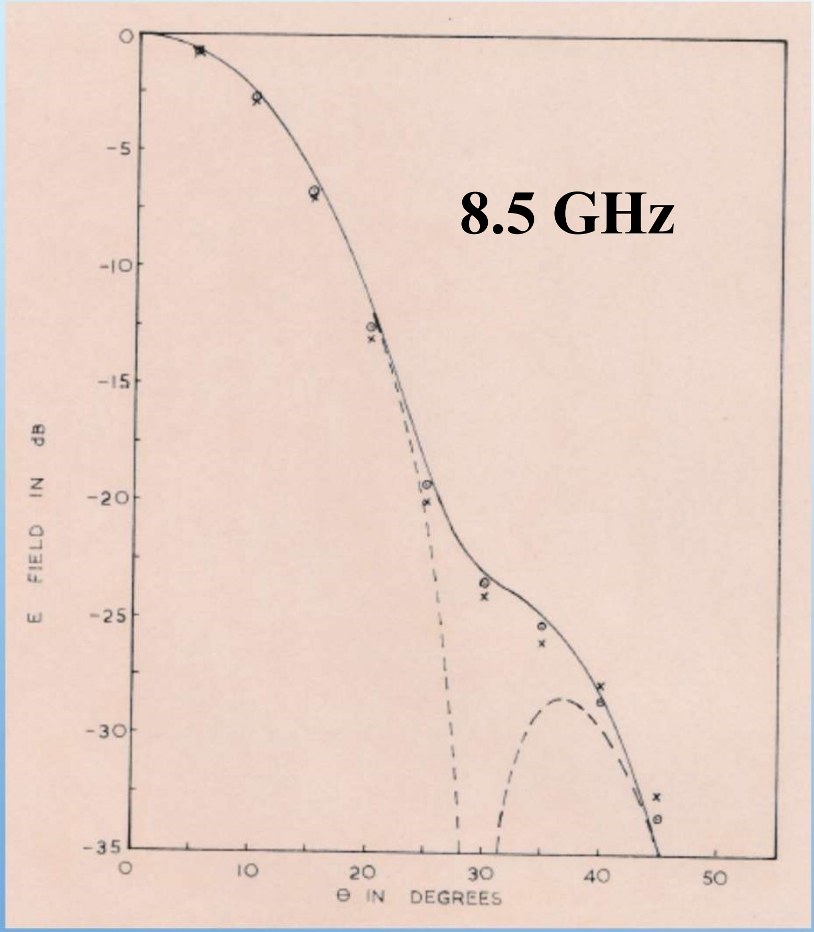
E-plane (——), H-plane (- - - -)
Beamwidths of HE_{11} Radiation Pattern of Corrugated Circular Waveguide as function of Normalized Frequency
($r_1/r_0 = 0.9$)

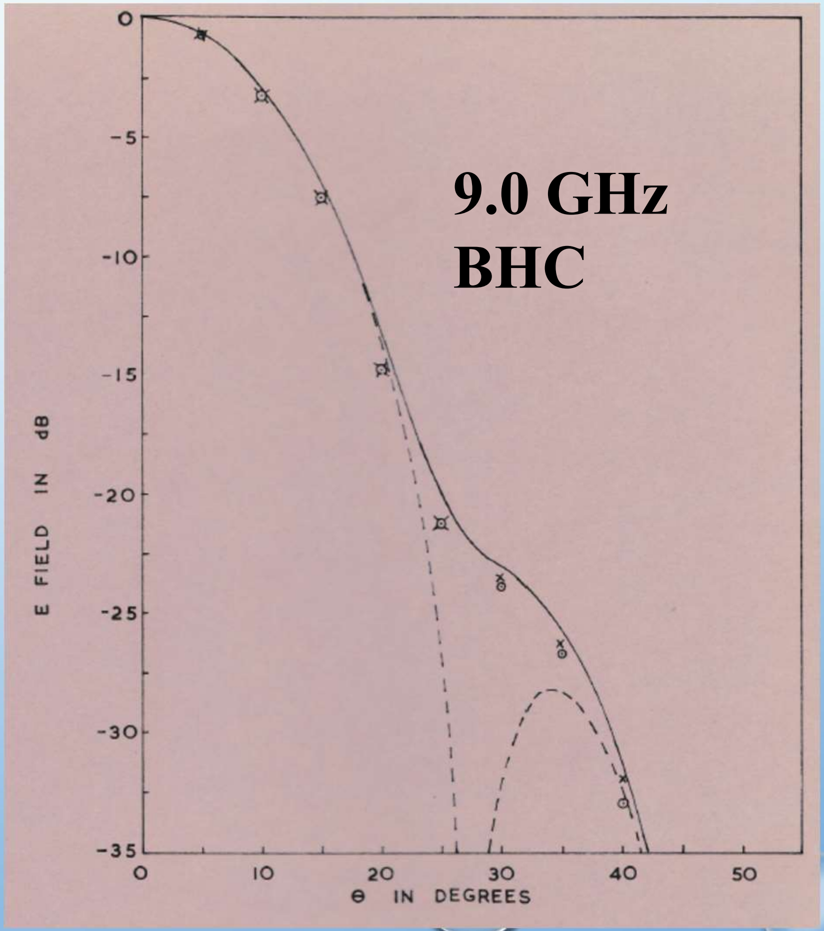
Narrow Flare Corrugated Conical Horn

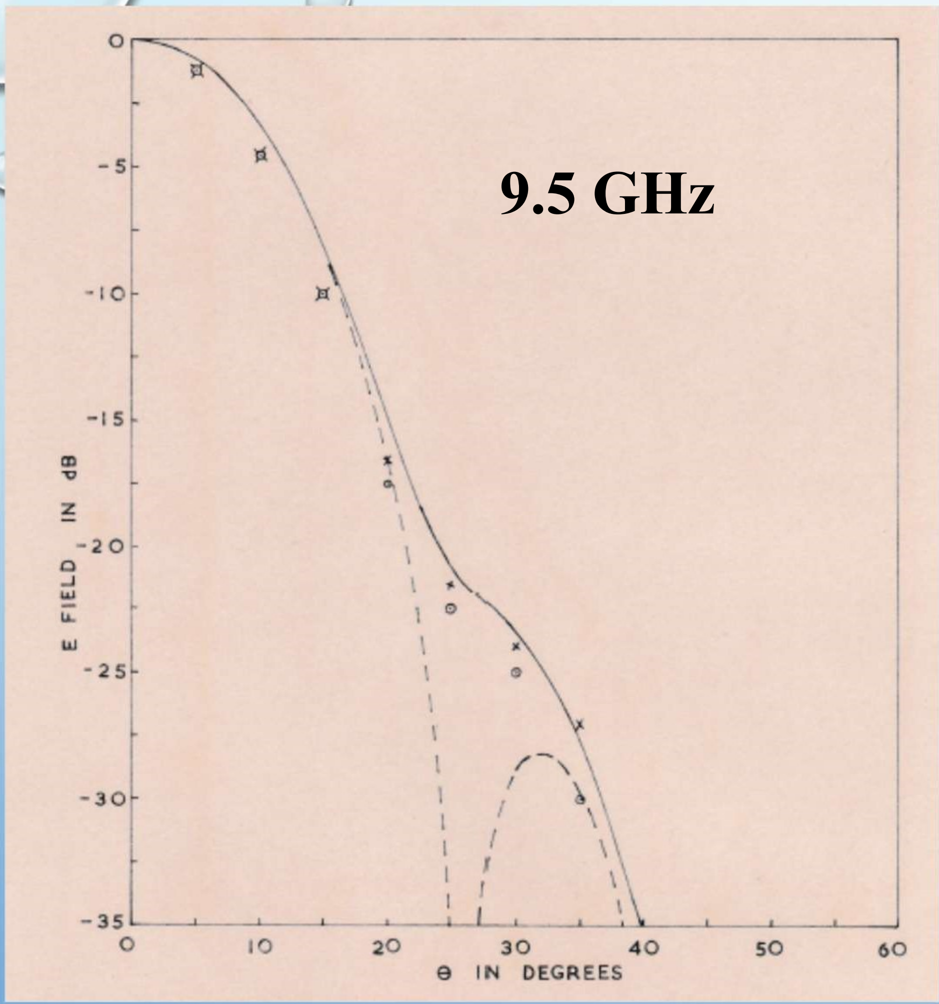


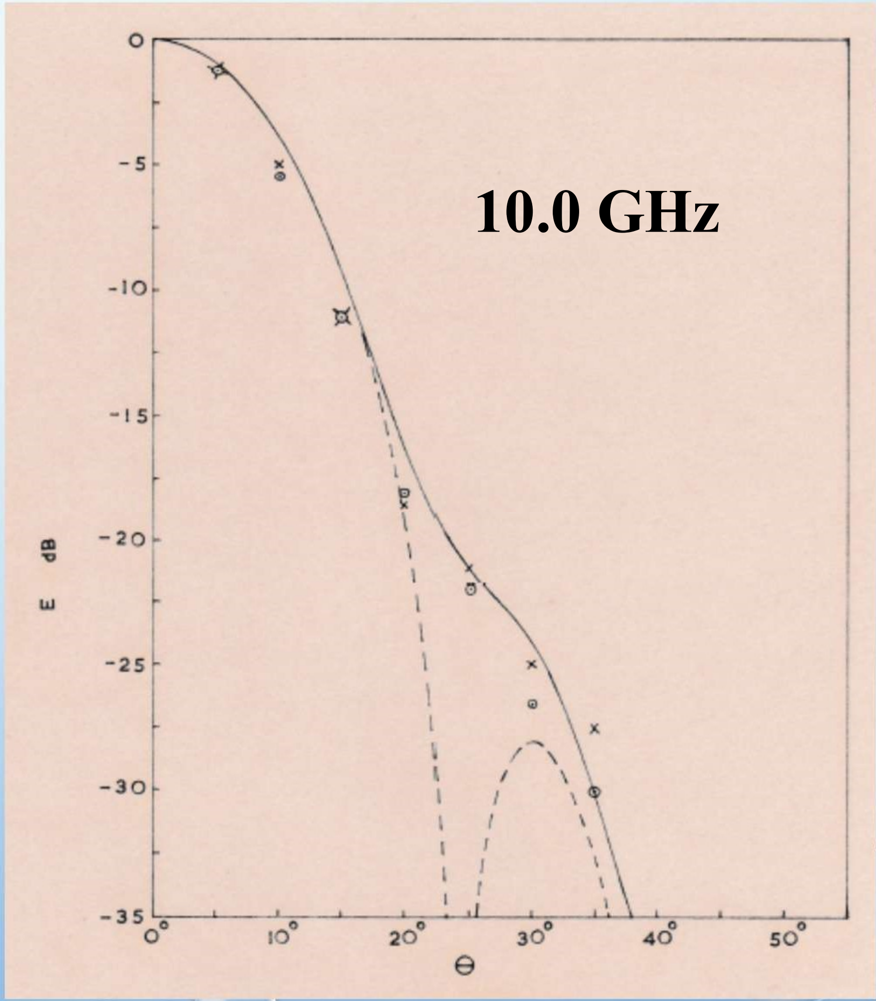
Experimental X-Band 12^{o} Half Flare Corrugated Horn

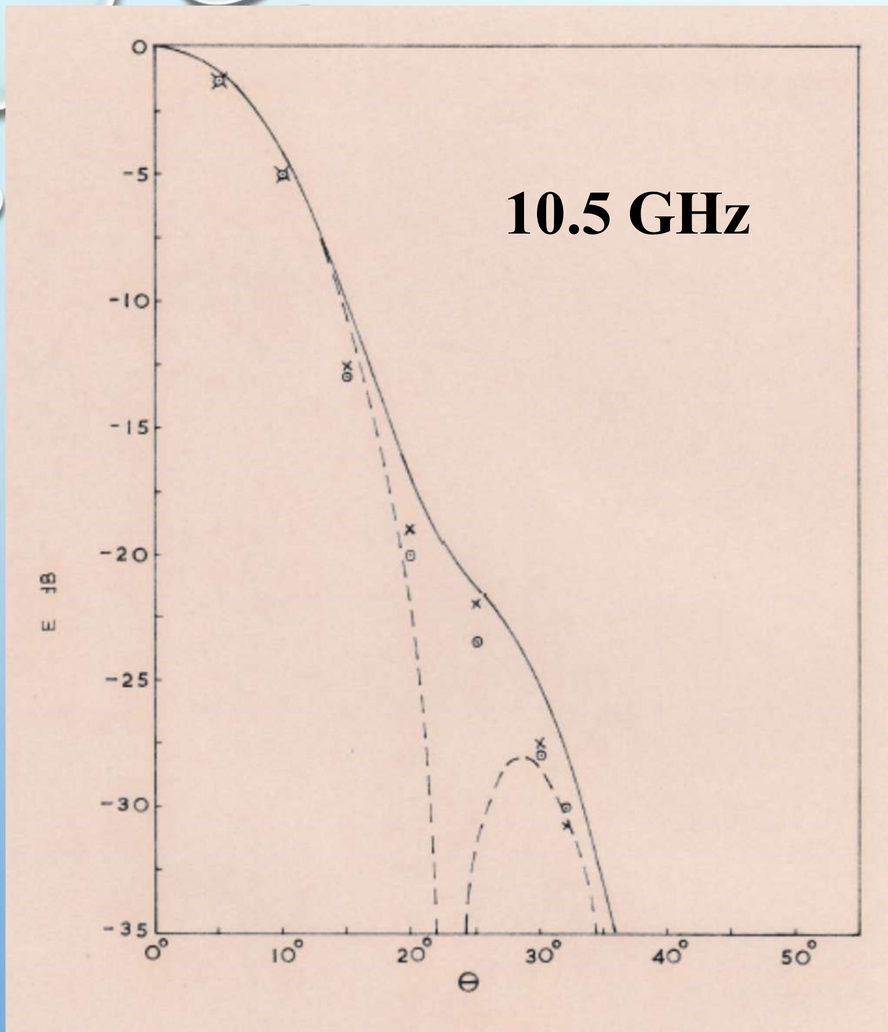
Theoretical and Measured Patterns of Experimental 12° Half Flare Horn

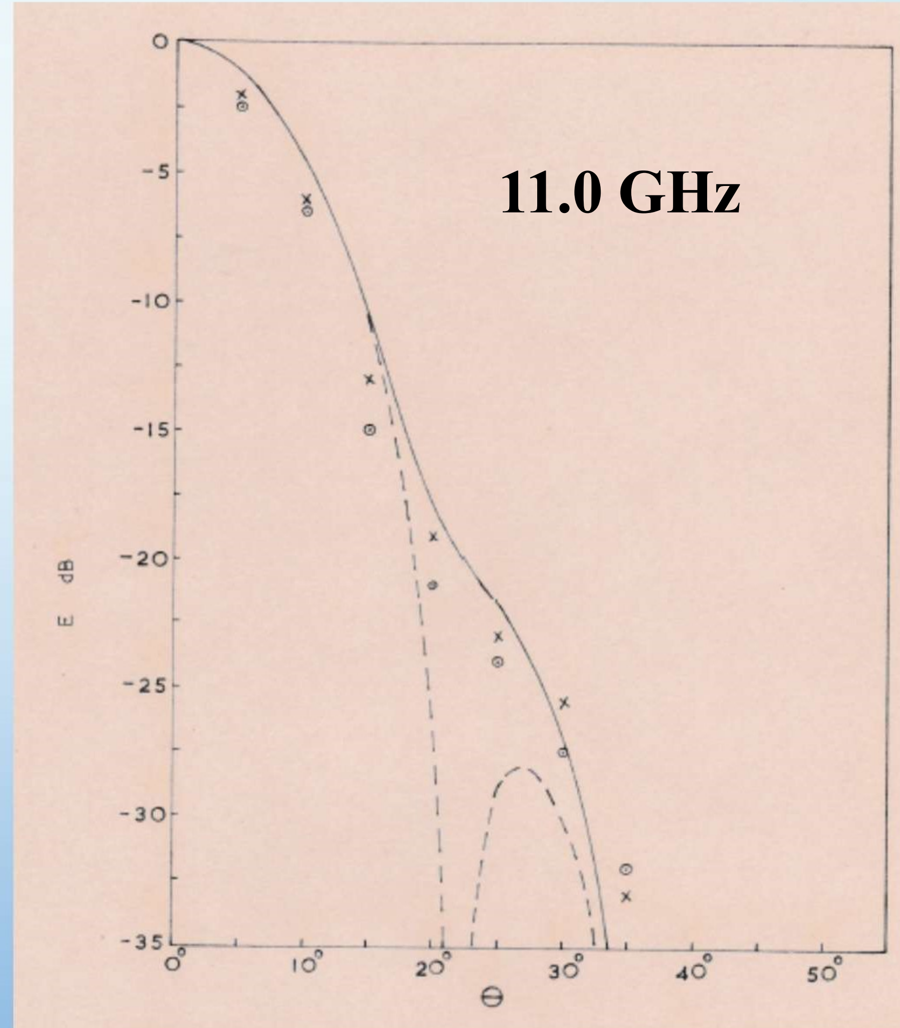


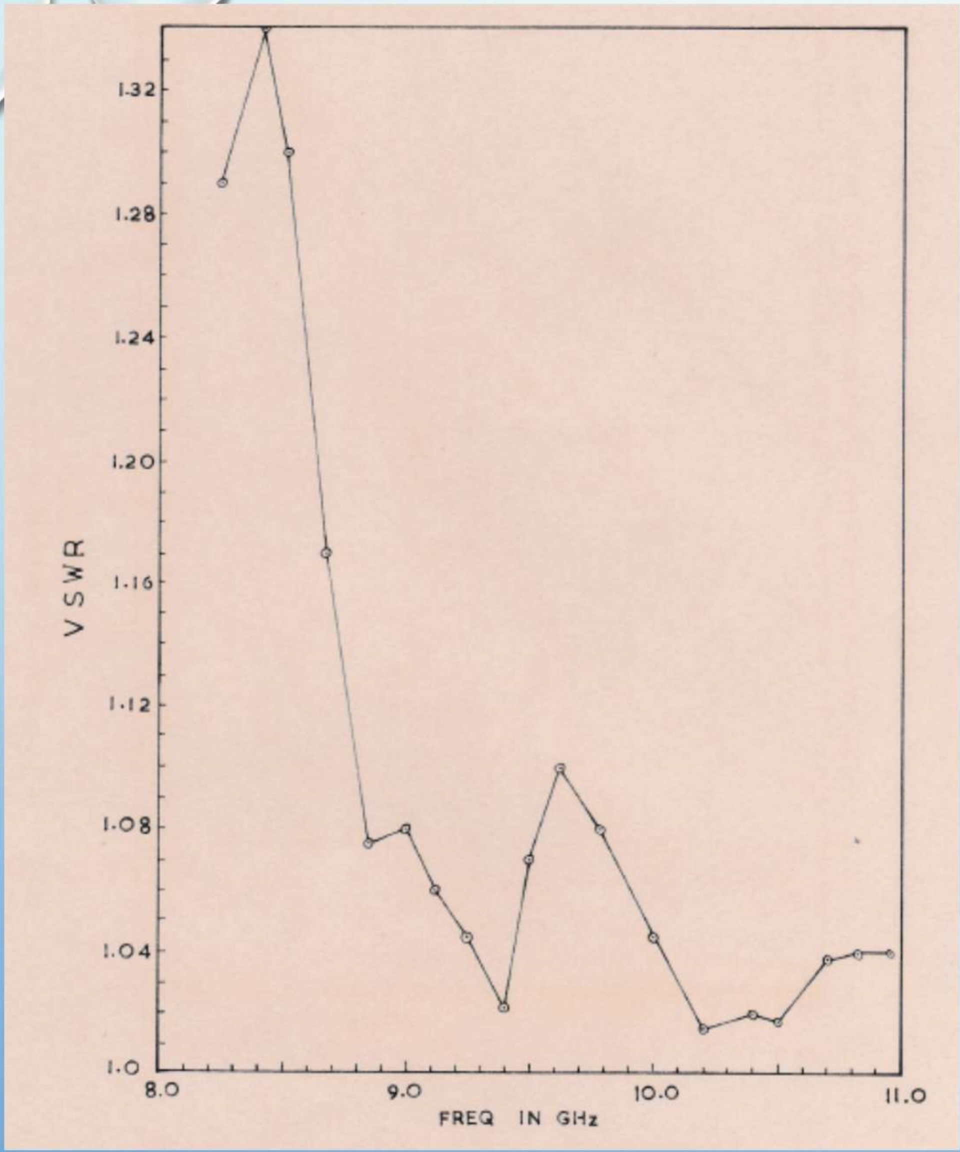



9.5 GHz
E FIELD IN dB
θ IN DEGREES
0
-5
-10
-15
-20
-25
-30
-35
0
10
20
30
40
50
60

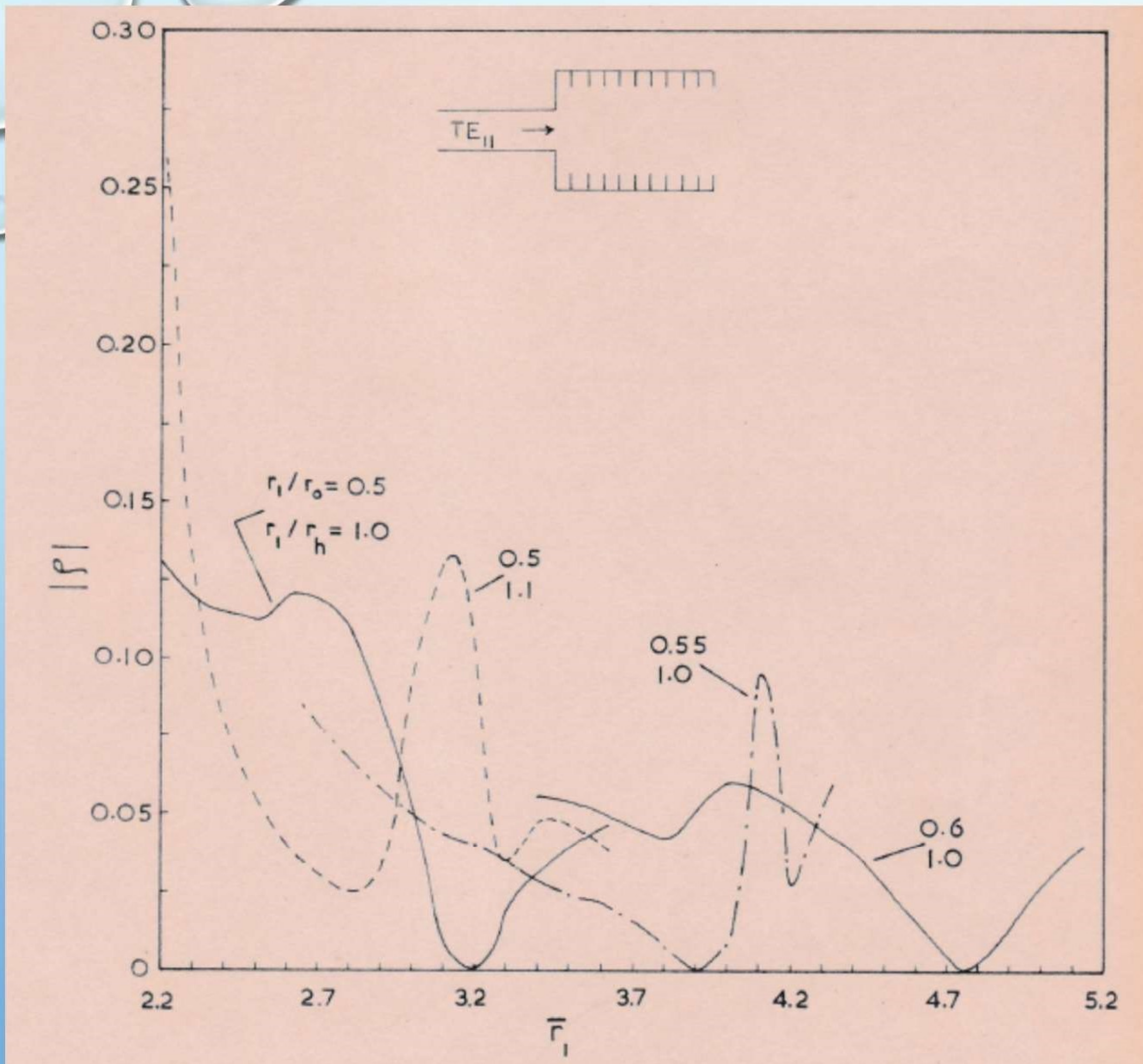

10.0 GHz
E dB
Θ
0
-5
-10
-15
-20
-25
-30
-35
0°
10°
20°
30°
40°
50°


10.5 GHz
0
-5
-10
-15
-20
-25
-30
-35
E dB
0°
10°
20°
30°
40°
50°
Θ


11.0 GHz
0
-5
-10
-15
-20
-25
-30
-35
E dB
0°
10°
20°
30°
40°
50°
Θ



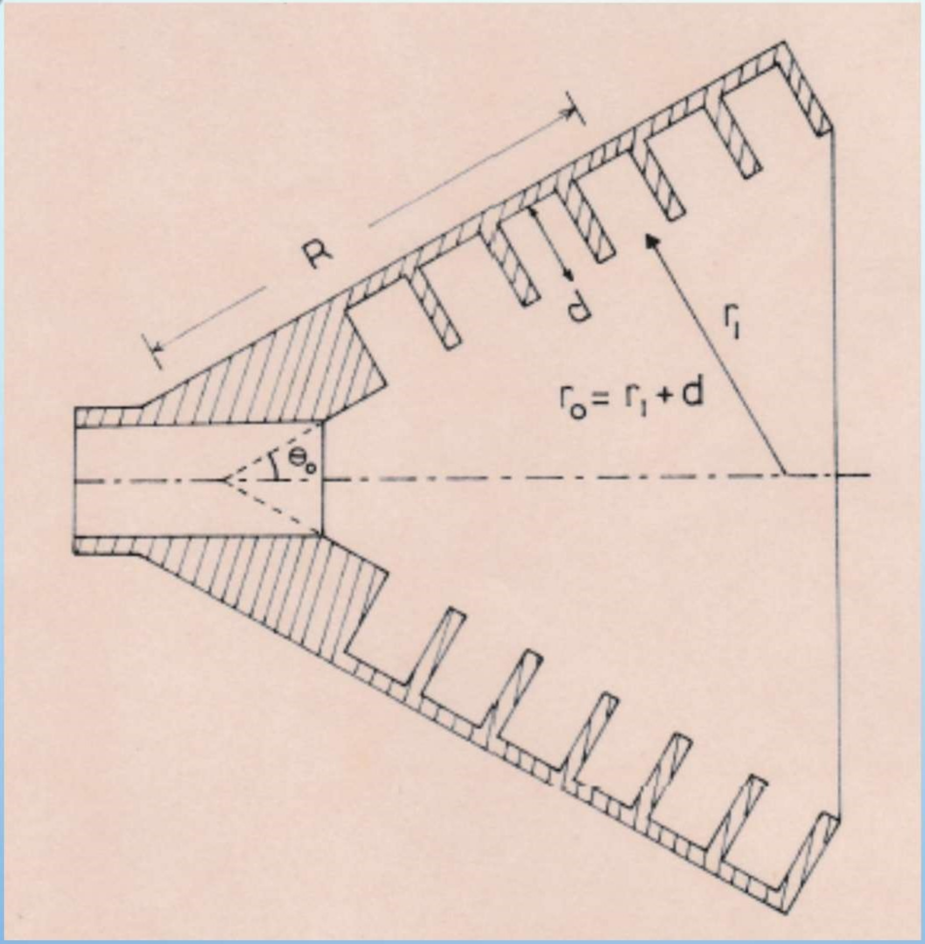
Measured Input VSWR at the throat of the Experimental Narrow Flare Horn of 12^{o} Half Flare Angle as Function of Frequency



Theoretically computed Reflection Coefficient at the junction of a TE_{11} circular waveguide and a corrugated circular waveguide as a function of normalized frequency for various waveguide parameters

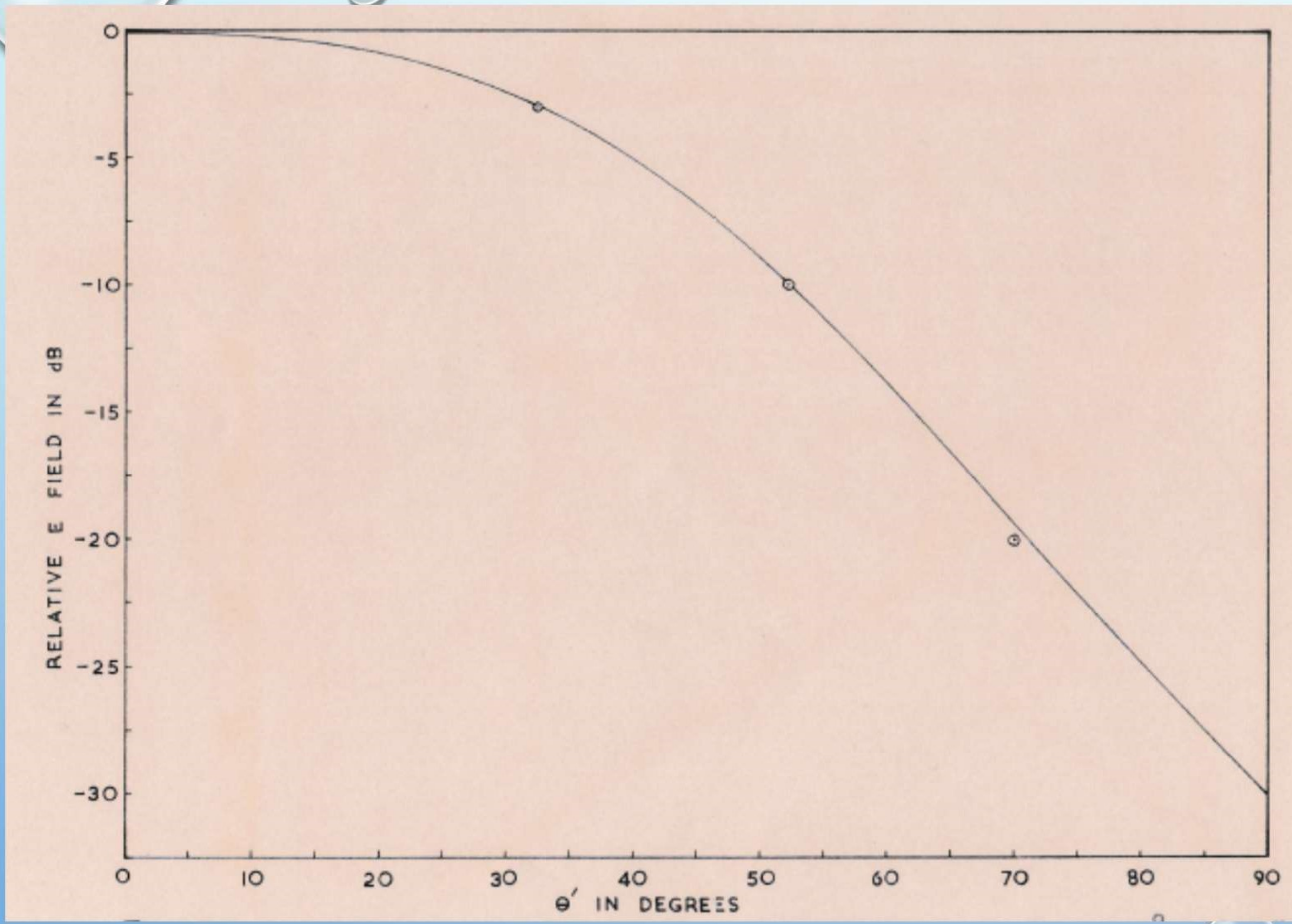
Propagation and Radiation Characteristics of Wide-flare Corrugated Conical Horn

- Spherical Hybrid Modes in the Horn and Aperture Field
- Far-field pattern by vector diffraction
- Radiation Field by Spherical Wave Expansion
- Computation of Phase-Centre Location
- Lens-corrected Scalar Feed
- Performance of Parabolic Reflector with Scalar Feed
- An Experimental 30^{o} Half-Flare Corrugated Conical Horn
- Experimental Results
- Modified Scalar Horn with Corrugations only near Aperture

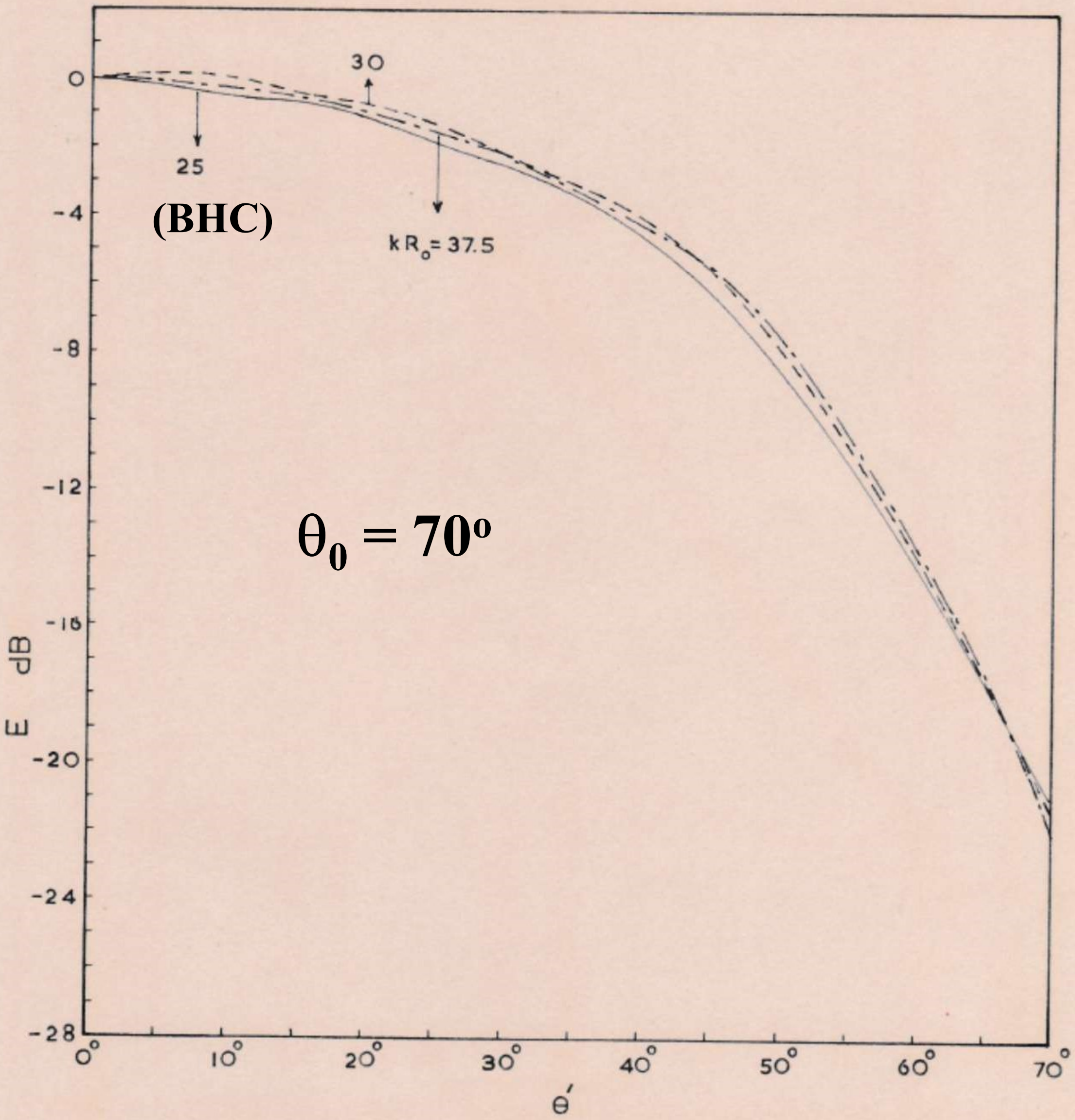


Wide Flare Corrugated Conical Horn

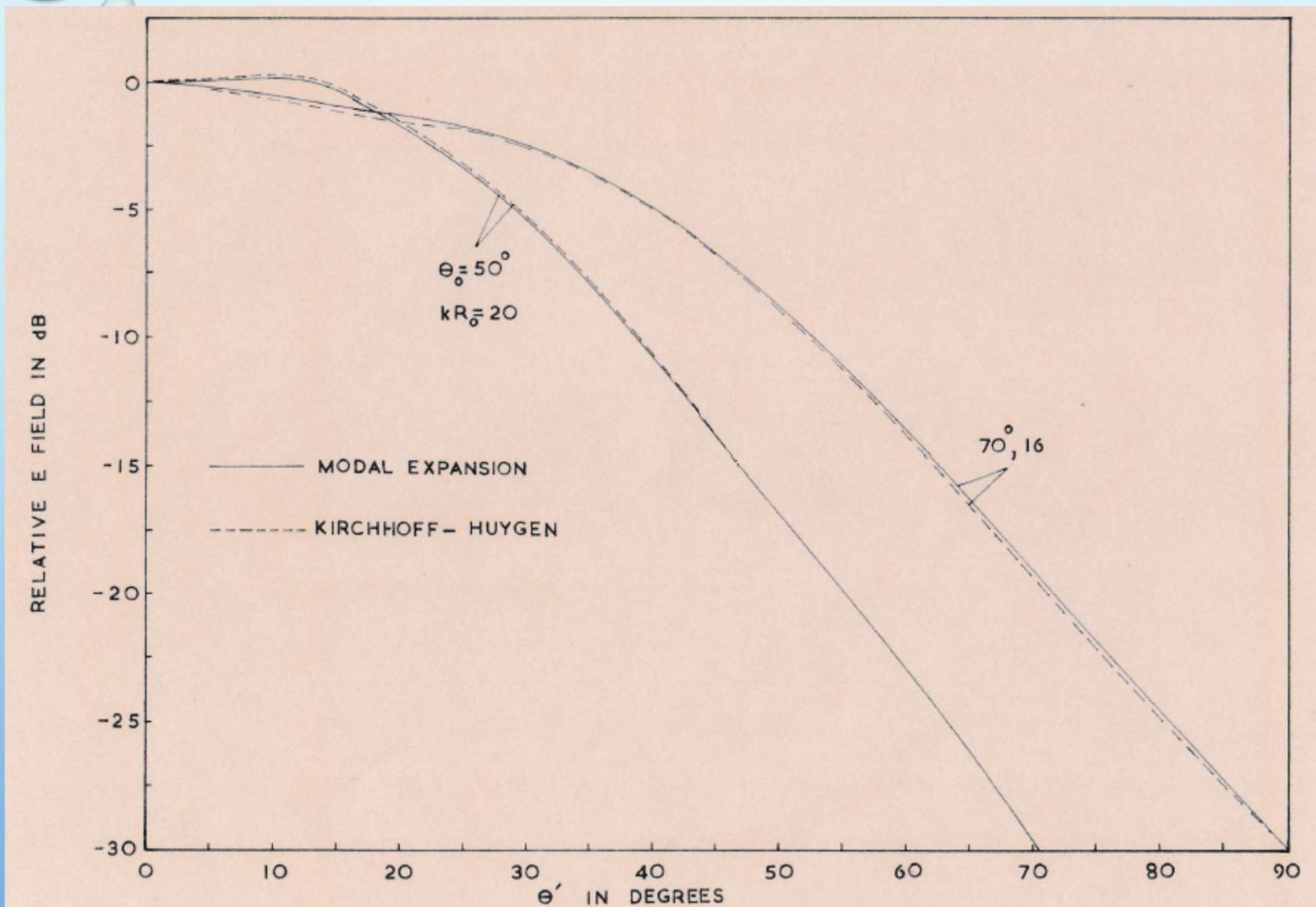
Impedance boundary condition becomes function of R.



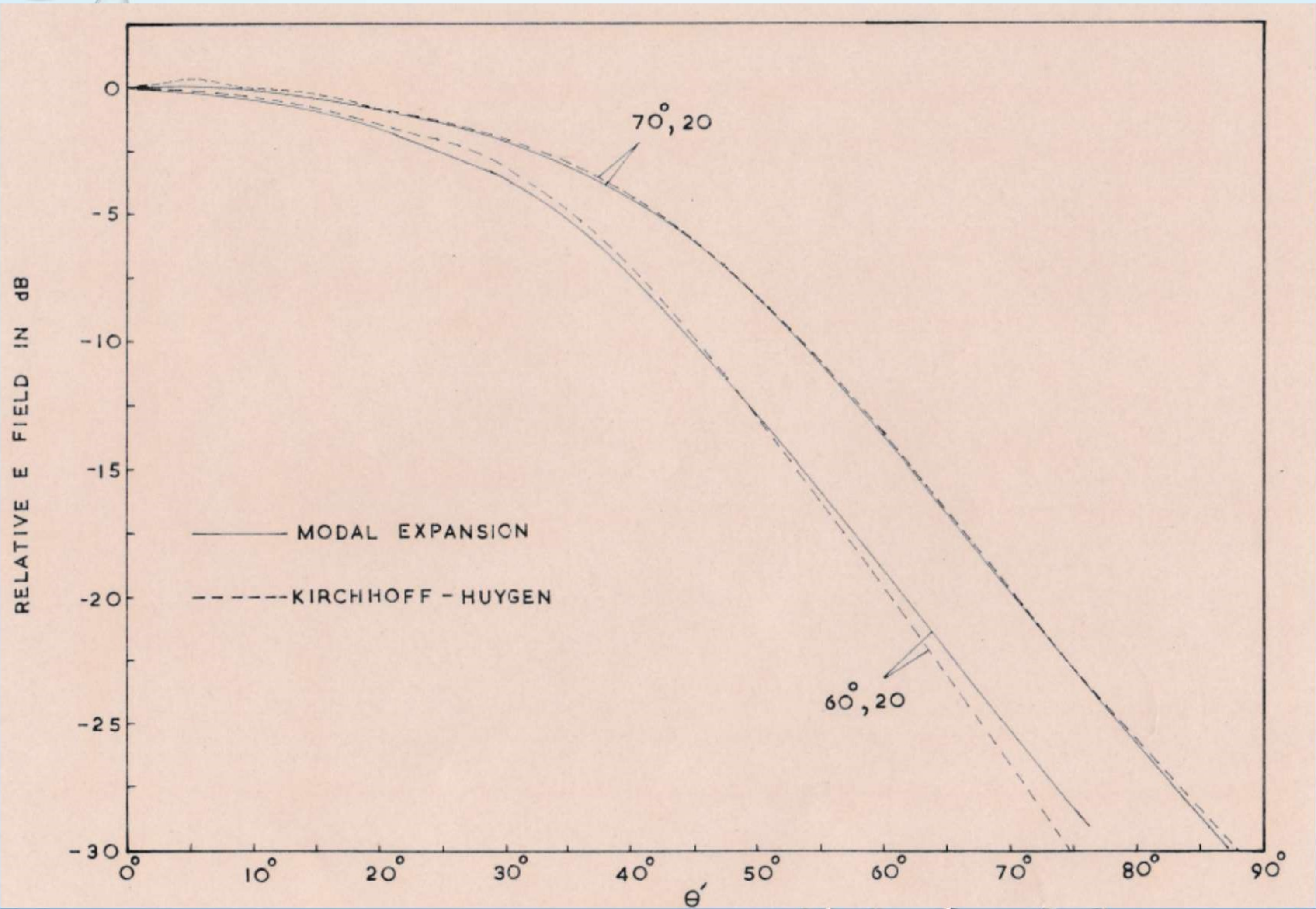
Theoretical Radiation Pattern of Corrugated Horn of 70^{o} Half Flare Angle agrees almost exactly with experimental data of Kay's Scalar Horn



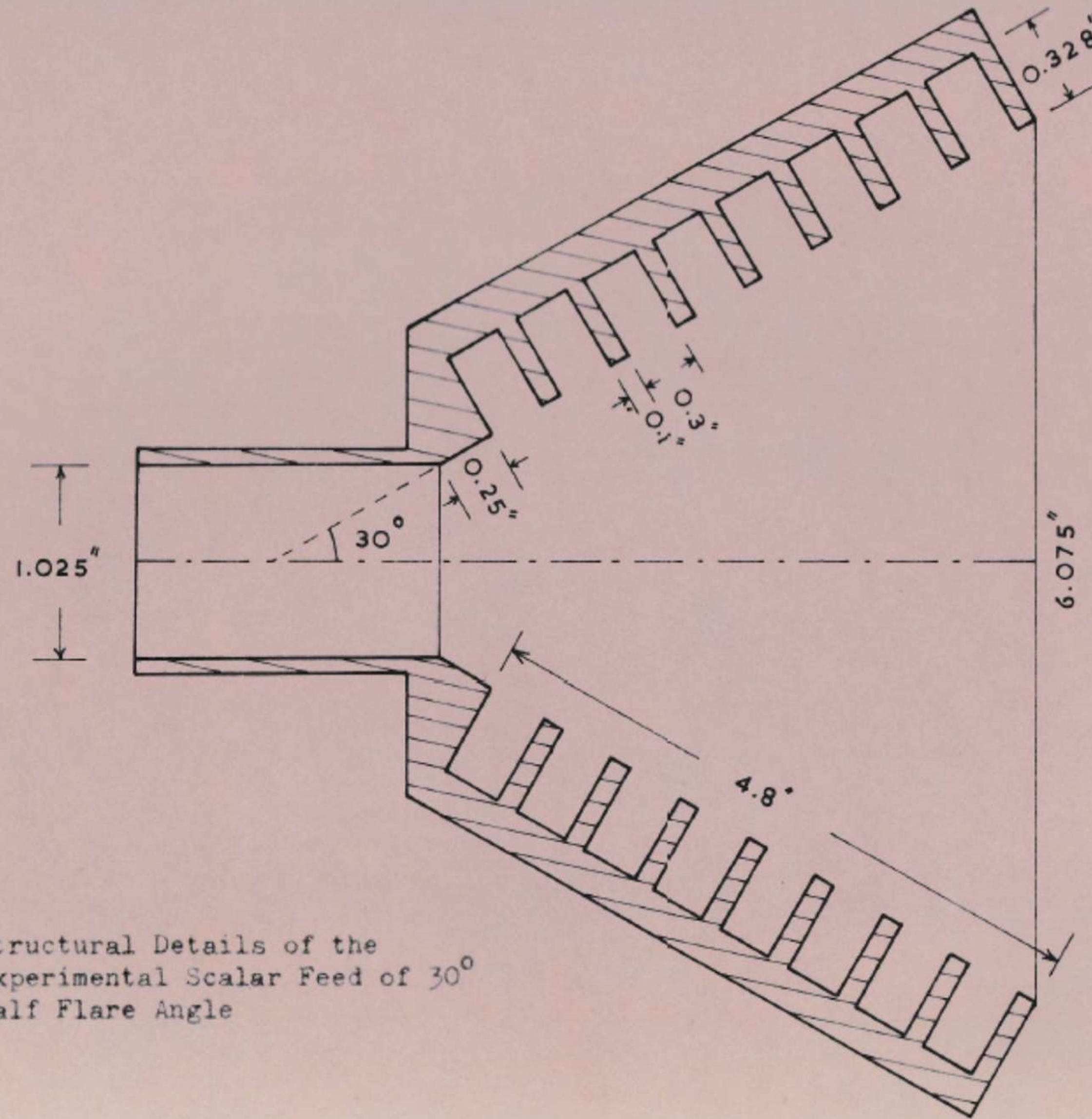
30
25
(BHC)
kR_o = 37.5
$\theta_0 = 70^o$
E dB
0
-4
-8
-12
-16
-20
-24
-28
0°
10°
20°
30°
40°
50°
60°
70°
θ'



RELATIVE E FIELD IN dB
0
-5
-10
-15
-20
-25
-30
0
10
20
30
40
50
60
70
80
90
θ′ IN DEGREES
θ₀= 50°
kR₀= 20
70°, 16
MODAL EXPANSION
KIRCHHOFF- HUYGEN



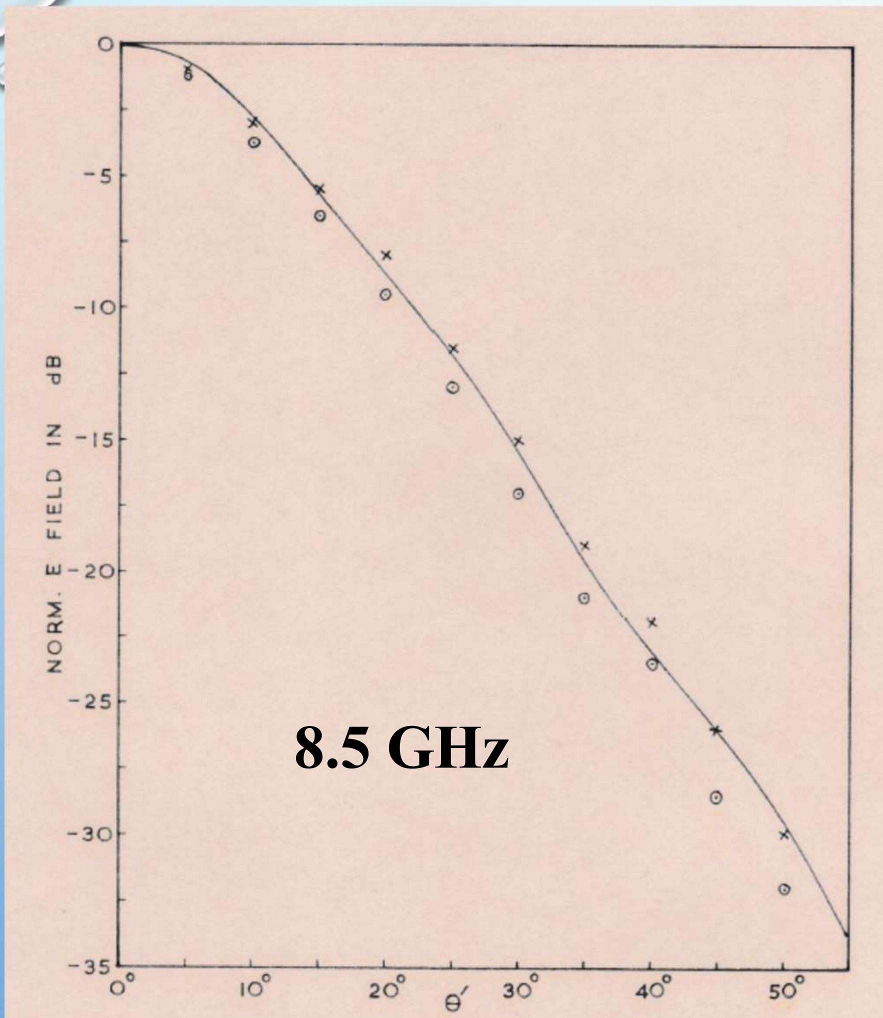
0
-5
-10
-15
-20
-25
-30
RELATIVE E FIELD IN dB
70°, 20
60°, 20
MODAL EXPANSION
KIRCHHOFF - HUYGEN
0°
10°
20°
30°
40°
50°
60°
70°
80°
90°
θ′

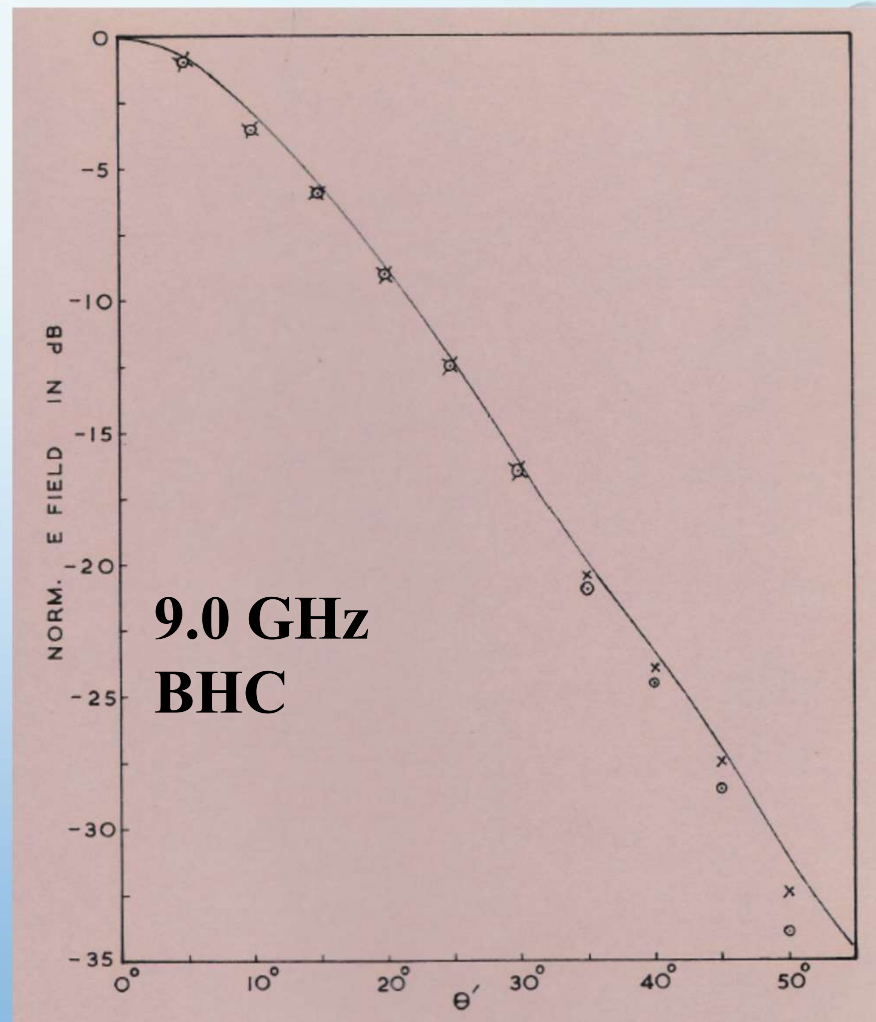


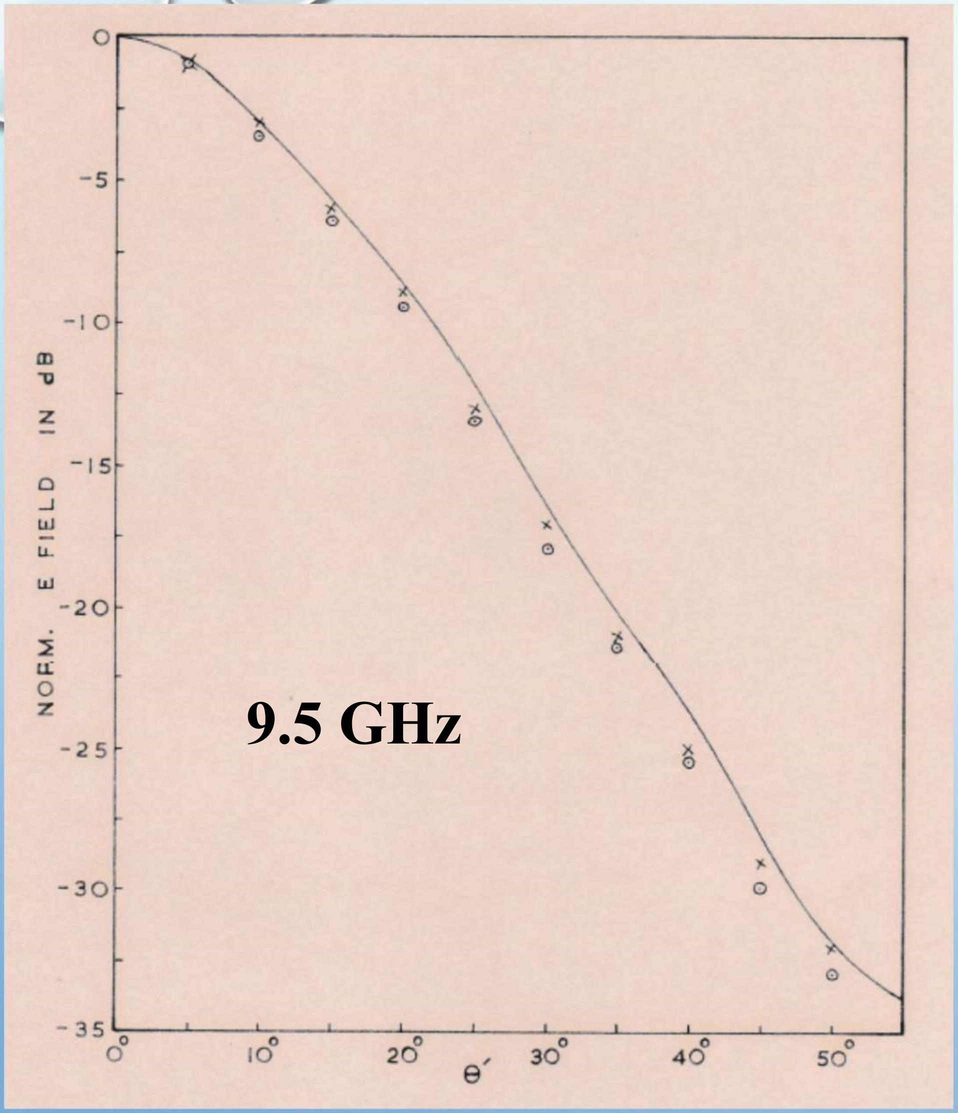
Structural Details of the
Experimental Scalar Feed of 30°
Half Flare Angle

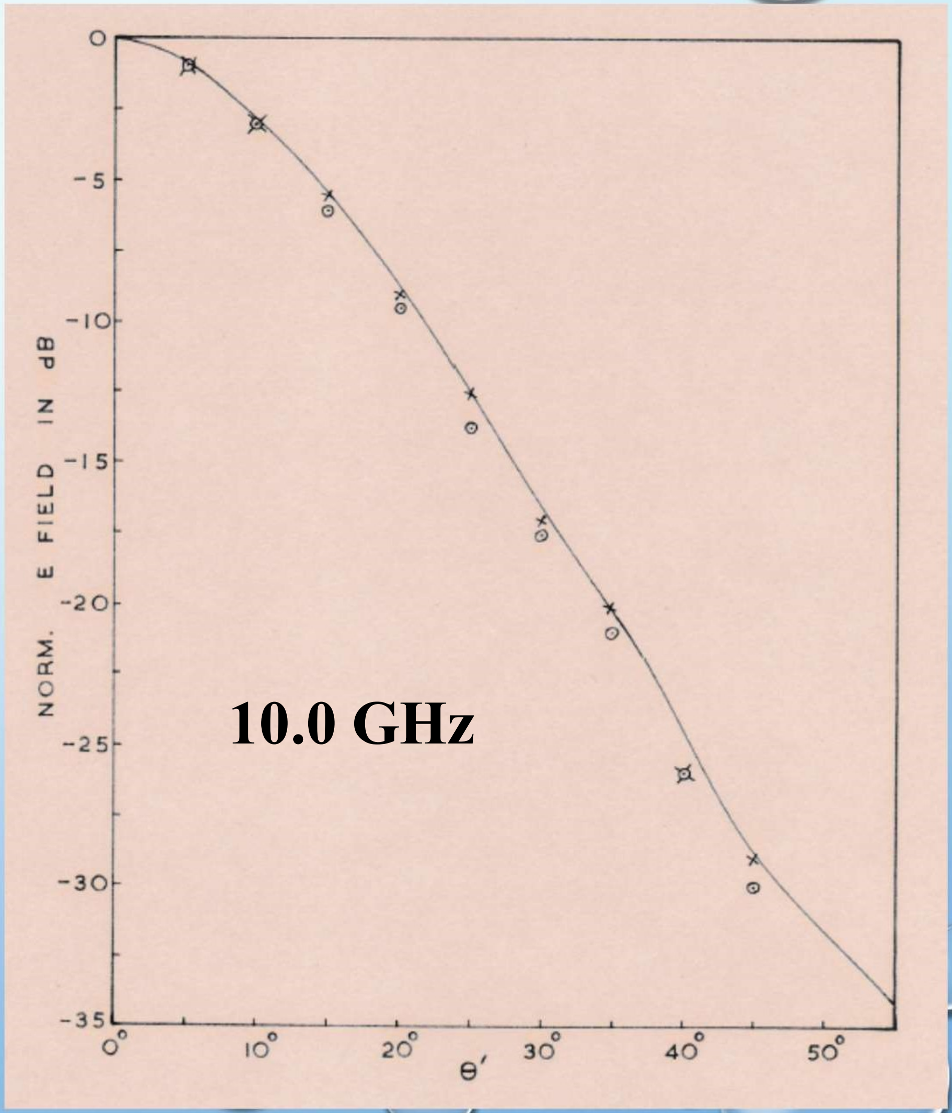
Structural Details of the Experimental Scalar Feed of 30° Half Flare Angle

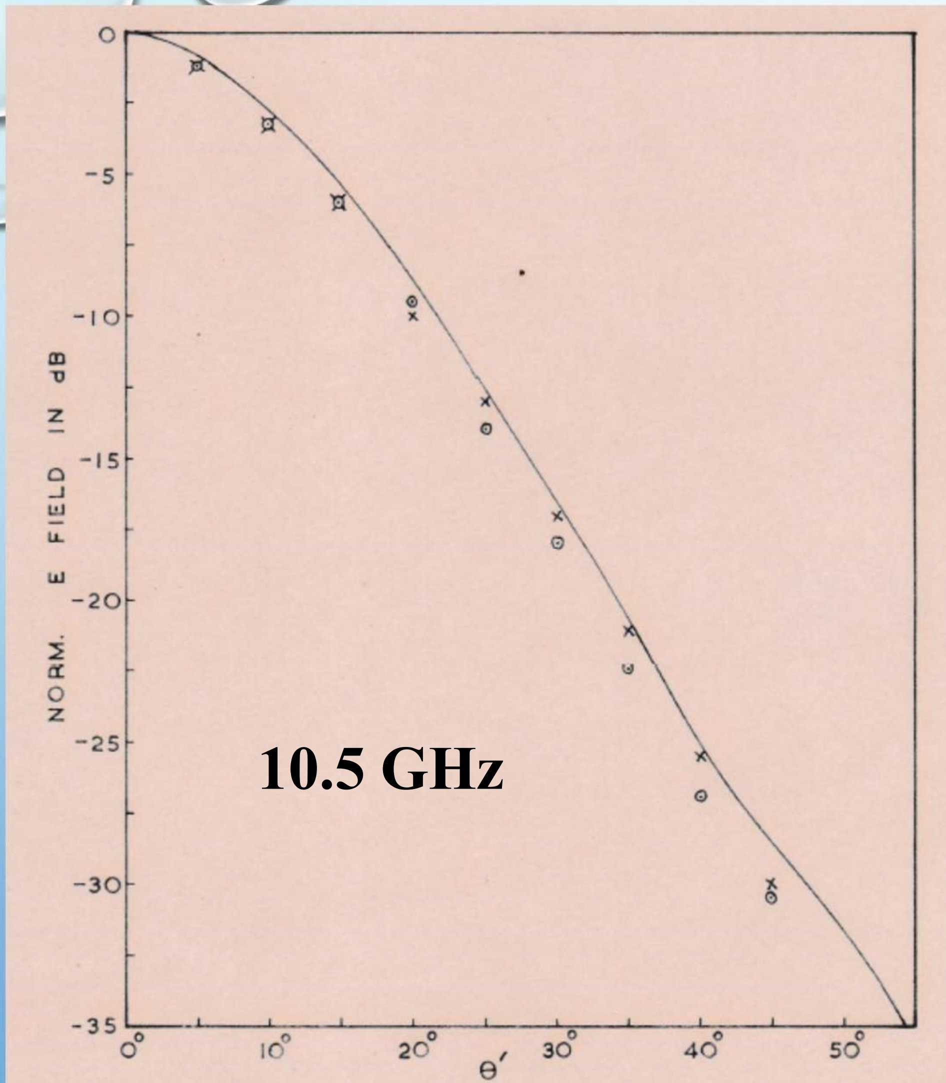
Theoretical and Measured Patterns of Experimental 30^o Half Flare Horn



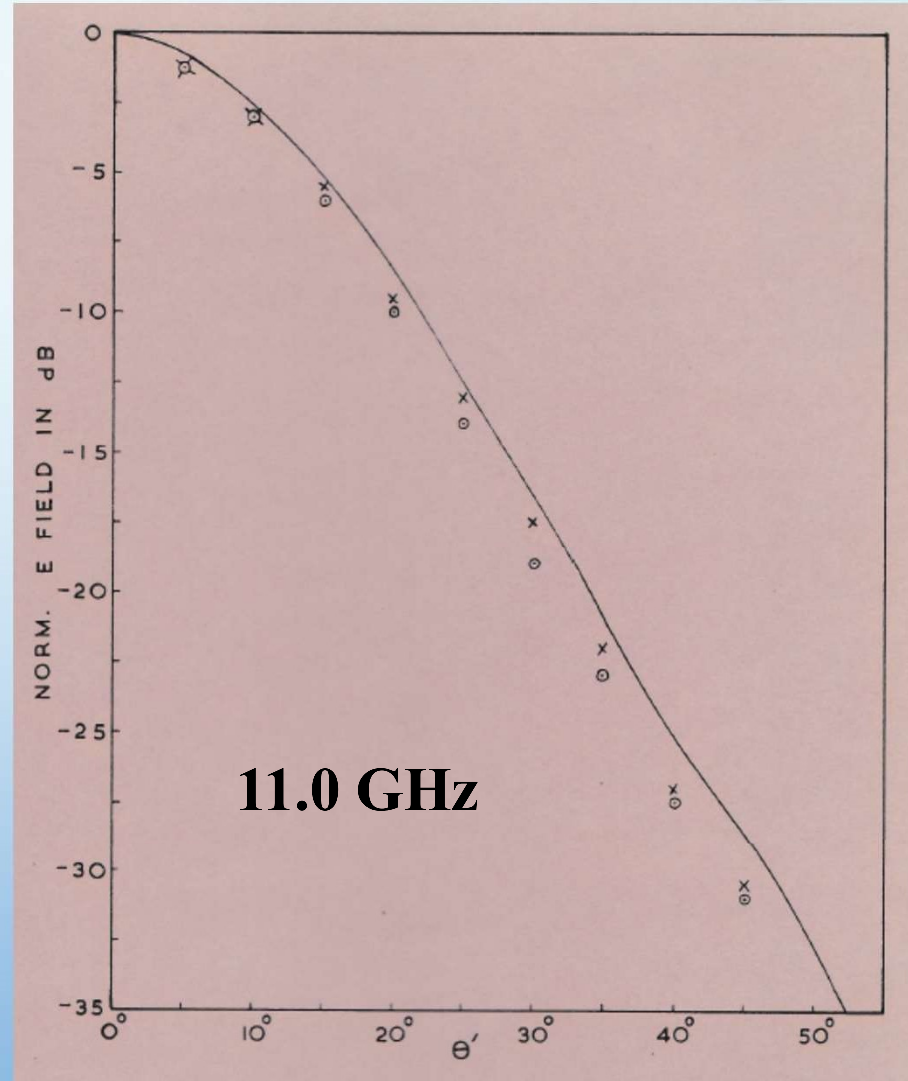



0
-5
-10
-15
-20
-25
-30
-35
NORM. E FIELD IN dB
0°
10°
20°
30°
40°
50°
θ′
9.5 GHz


0
-5
-10
-15
-20
-25
-30
-35
NORM. E FIELD IN dB
0°
10°
20°
30°
40°
50°
θ′
10.0 GHz

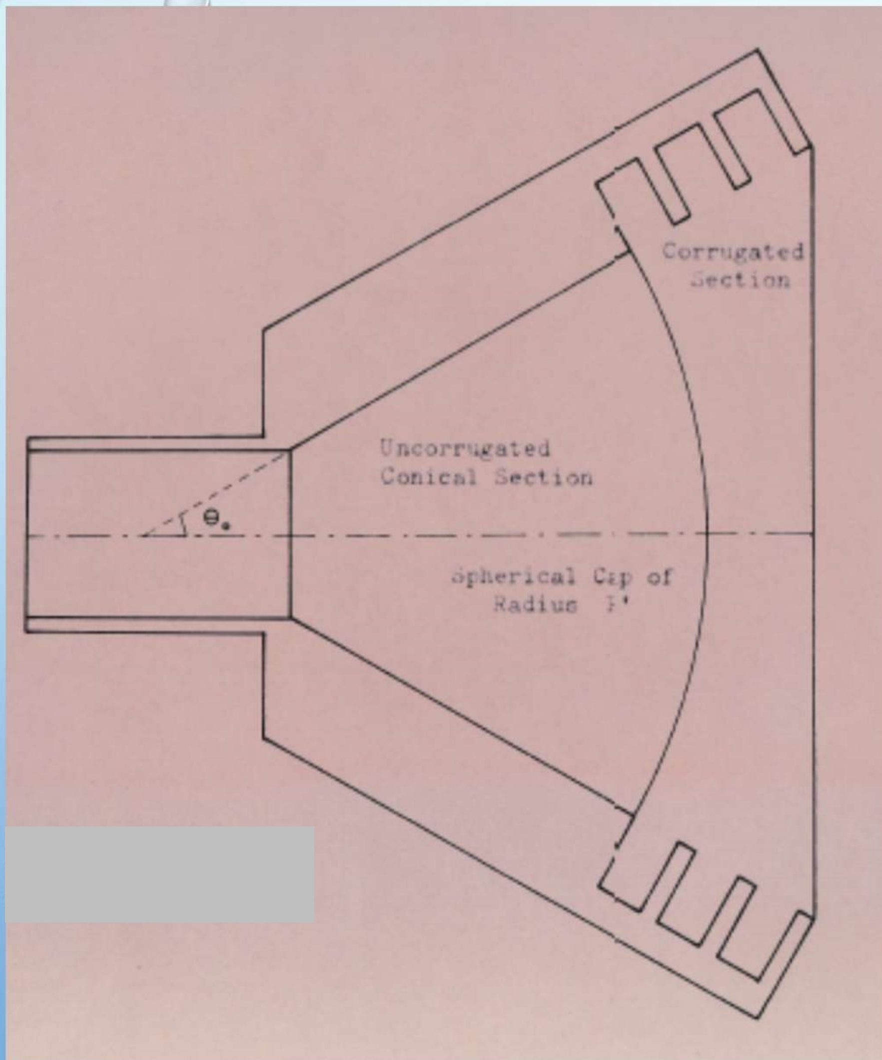


0
-5
-10
-15
-20
-25
-30
-35
NORM. E FIELD IN dB
0°
10°
20°
30°
40°
50°
θ′
10.5 GHz



0
-5
-10
-15
-20
-25
-30
-35
NORM. E FIELD IN dB
0°
10°
20°
30°
40°
50°
θ′
11.0 GHz

Measured Input VSWR at the throat of the Experimental Wide Flare Horn of 30° Half Flare Angle as Function of Frequency



Modified Wide-Flare Corrugated Conical Horn with Corrugations only near the Aperture

Excitation of Hybrid Modes in Corrugated section was computed by mode matching over the spherical cap at the junction.

Excitation of Modified Conical Scalar Horn
P_m/P_{in} in for first six modes

m	P_m/P_{in} in per cent				
	$\theta_o = 30^o$	$\theta_o = 40^o$	$\theta_o = 50^o$	$\theta_o = 60^o$	$\theta_o = 70^o$
1	83.87	83.36	82.67	81.79	80.67
2	4.39	4.56	4.80	5.11	5.53
3	3.59	3.69	3.81	3.96	4.13
4	1.36	1.40	1.46	1.54	1.64
5	1.27	1.31	1.35	1.41	1.49
6	0.68	0.70	0.73	0.76	0.81

Modified Scalar Feed: Observations from Computed results

- Mode-matching equations were solved with 6 modes each in corrugated and un-corrugated sections for different flare angles.
- The reflection coefficient of the incident TE_{11} mode and excitation of higher order modes in un-corrugated section are negligible.
- The fraction of the incident power transferred to the modes in the corrugated section decreases sharply for the higher order modes and is less than 1% for the 6^{th} mode.

Thank You