A Conical Dielectric-Loaded Horn with Symmetrical Radiation Pattern

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Abstract

A relatively broadband dual-mode conical horn, which has a symmetrical radiation pattern and extremely low sidelobes, can be obtained by loading a dielectric layer inside the feedhorn. An investigation of the radiation behaviour of conical horn antenna with small flare angle is described. Measured radiation characteristics in the X-frequency band are shown.

Keywords:
dual-mode feed, symetrical radiation pattern

1. Introduction

During recent years two main problems have concerned feed designers, namely, high efficiency and low cross-polarization. Design features of the overall antenna such as low sidelobes and low input VSWR are also important but, especially in dual-reflector systems, these are influenced more by the design of the reflector and subreflector than by the feed. It is well known that the conical horn, operating in the dominant TE_{11} mode, has effectively tapered aperture distribution in the electric plane. For raising aperture efficiency of feeds excited by the TE_{11} mode, we mention that in narrow-bandwidth applications, very high efficiencies can be achieved through the use of multimode feeds. In 1963, Potter [2] proposed the use of a dual-mode horn utilizing TE_{11} and TM_{11} modes in order to produce a more nearly circularly symmetric radiation pattern. These two modes are then excited in the horn aperture with the appropriate relative amplitude and phase to effect sidelobe suppression and beamwidth equalization. Excitation of the TM_{11} mode in the horn has been considered by many authors, e.g. [2] - [4] . This paper describes the principle of a conical dual-mode horn antenna with small flare angle, operating in the X - frequency band, its structure and measured radiation patterns.

2. Excitation of TM_{11} mode in the horn

The $TE_{11} \rightarrow TM_{11}$ mode conversion may be accomplished by introducing a circularly symmetric perturbation into a section of circular waveguide preceding

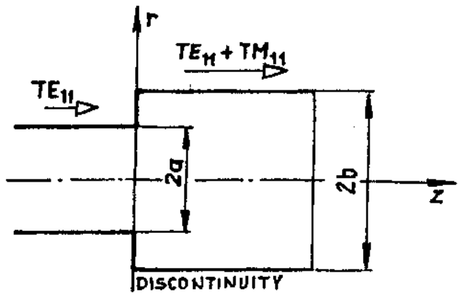

Fig.1
Mode conversion at a step

the horn throat. If the diameter of the input waveguide is chosen small enough so that it will not support TM_{11} mode over the frequency band, the configuration in Fig.1, behaves very well over a wide band. Such a discontinuity was used by Potter [2] in early experiments with dual-mode horn excitation.

The conversion coefficient at the discontinuity (z=0) can be determined as [3]

$$C = \left| \frac{E_r^{TM}}{E_r^{TE}} \right|_{(r=a,\varphi=0)} = 2,2\beta_{TM} a \int_0^1 \rho f(\rho) J_1(x_{11}\rho) d\rho \quad (1)$$

where

$\beta_{TM} = \sqrt{k^2 - k_c^2}$ - propagation constant of TM_{11} mode,

$\rho = \frac{r}{a}$ - normalised waveguide radius,

$x_{11} = k_c a = 3,83$ - 1st root of Bessel function,

$k = \frac{2\pi}{\lambda}$ - free space wavenumber,

and $f(\rho)$ decribes the radial dependence of E_Z.

In the design of dual-mode conical horns, it is necessary to specify conditions at the radiating aperture, since it is the field distribution at this cross section which determines the feed characteristics. The ratio of conversion coefficient at the aperture C_2 to coefficient C_1 at the cross section where conversion occurs is given by

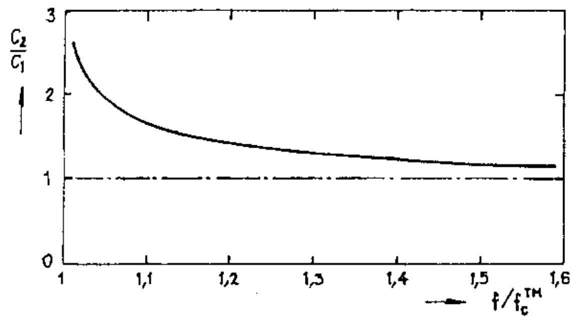

Fig.2
Ratio of coefficients at horn aperture and converter

$$\frac{C_2}{C_1}=\frac{f}{f_c^{TM}}\left\{\left[\left(\frac{f}{f_c^{TM}}\right)^2-1\right].\left[\left(\frac{f}{f_c^{TM}}\right)^2-0,23\right]\right\}^{-\frac{1}{4}} \quad (2)$$

where f_c^{TM} is the TM_{11} cutoff frequency at the cross section where conversion occurs. If we consider the X - frequency band, the dependence of ratio C_2/C_1 for $a = 11\,\mathrm{mm}$ and $b = 16\,\mathrm{mm}$ is plotted in Fig.2.

The relation (2) can be used if the following assumptions are made:

- the power transmitted in each mode is constant, i.e., the horn is lossless and no further conversion occurs,
- the transverse electromagnetic fields at any cross section of a narrow angle conical horn are approximately the same as in a circular waveguide,
- the aperture diameter is much larger than the cutoff diameter for the TM_{11} mode.

3. Dual-mode conical horn antenna

The dielectric-loaded conical horn antenna operating at end of X-band used in the experiments has these parameters:

- aperture diameter $D = 77,4$ mm
- horn flare half angle $\alpha = 9,5^o$
- length along horn wall $L = 238$ mm
- waveguide diameter $2a = 22$ mm

The structure of dielectric-loaded horn antenna is shown in

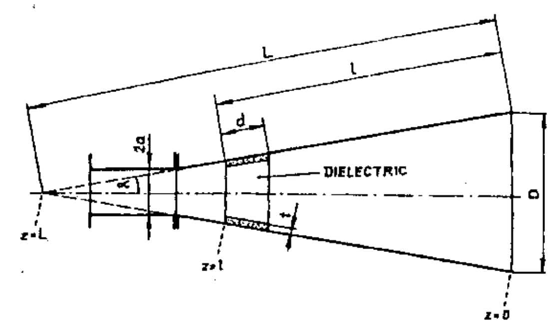

Fig.3
Conical dielectric-loaded horn antenna

Fig.3. The dielectric material used throughout is Teflon with relative permitivity $\varepsilon_r = 2,1$ and thickness $t = 2$ mm.

Phase progression of waves propagating in a horn with small flare angle can be calculated as that in waveguide with continuously changing diameter [3] . The distance between successive minima both of waves TE_{11} and TM_{11} is

$$\Delta=\frac{2\pi}{\beta_{TE}-\beta_{TM}}=\frac{\lambda_9^{TE}.\lambda_9^{TM}}{\lambda_9^{TM}-\lambda_9^{TE}} \quad (3)$$

where $\lambda_9^{TE}, \lambda_9^{TM}$ are the guide wavelengths.

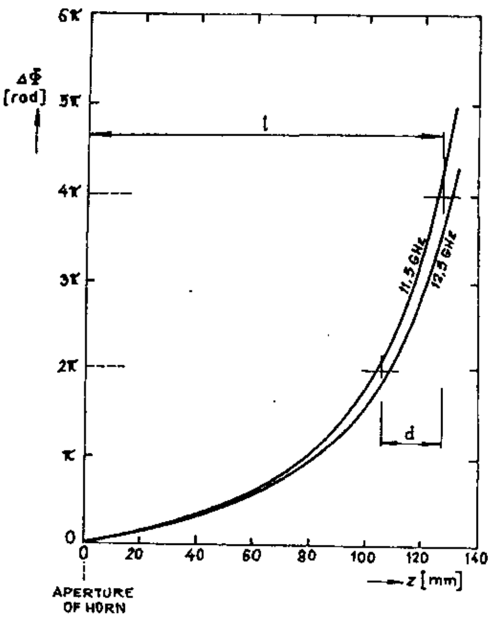

Fig.4
Phase difference between TE_{11} and TM_{11} modes along horn wall

Propagation constants in the horn antenna for TE_{11} and TM_{11} modes can be calculated by [6]

$$\beta_{TE}(z)=\sqrt{k^2-\left[\frac{x_{11}'}{(L-z)\sin\alpha}\right]^2} \tag{4}$$

$$\beta_{TM}(z)=\sqrt{k^2-\left[\frac{x_{11}}{(L-z)\sin\alpha}\right]^2} \tag{5}$$

where coordinate z = 0 is at the aperture, $x_{11}'=1,841$, $x_{11}=3,832$ are 1st roots of J_1' and J_1, respectively. Then the phase difference between both of modes is

$$\Delta\Phi=(\beta_{TE}-\beta_{TM})z \tag{6}$$

Fig. 4 shows the calculated curves for the phase difference between TE_{11} and TM_{11} modes within a conical horn.

Both modes are set in phase at the horn aperture. It is of interest to note that a condition $\Delta\Phi=2n\pi$ with n = 0, 1,2,..., is satisfied even in a horn. A dielectric mode generator can be located inside the horn at the point where the curve gives $\Delta\Phi=2n\pi$.

4. Radiation from the conical horns

The radiation characteristics of the dominant TE_{11} mode and the TM_{11} mode in conical horns are worthy of detailed consideration. The following analysis is based on work by Silver [1] who developed the radiation functions for open-ended circular cross-section pipe, assuming to be equivalent to a conical horn with small flare angle. We consider that all noncompensated conical horns radiate in both the TE_{11} and TM_{11} modes. The polar and azimuthal component radiation patterns of the TE_{11} mode, if the aperture is assumed perfectly matched to free space, are given by Silver [1] as follows:

$$E_\theta^{TE}=-\frac{\varpi\mu}{2R}\left(1+\frac{\beta_{TE}}{k}\cos\theta\right)\cdot$$
$$\cdot J_1(k_c^{TE}a)\frac{J_1(ka\sin\theta)}{\sin\theta}\sin\Phi e^{-jkR} \tag{7}$$

$$E_\Phi^{TE}=-\frac{ka\varpi\mu}{2R}\left(\frac{\beta_{TE}}{k}+\cos\theta\right)\cdot$$
$$\cdot J_1(k_c^{TE}a)\frac{J_1'(ka\sin\theta)}{1-\left(\frac{k\sin\theta}{k_c^{TE}}\right)^2}\cos\Phi e^{-jkR} \tag{8}$$

where $k_c^{TE}=\sqrt{k^2-\beta_{TE}^2}$ is transverse wavenumber for the TE_{11} mode, and R, θ,Φ are a spherical coordinates in Fraunhofer zone. The radiation patterns of the unloaded conical horn calculated as for waveguide, with considered parameters, are shown in Fig.5.

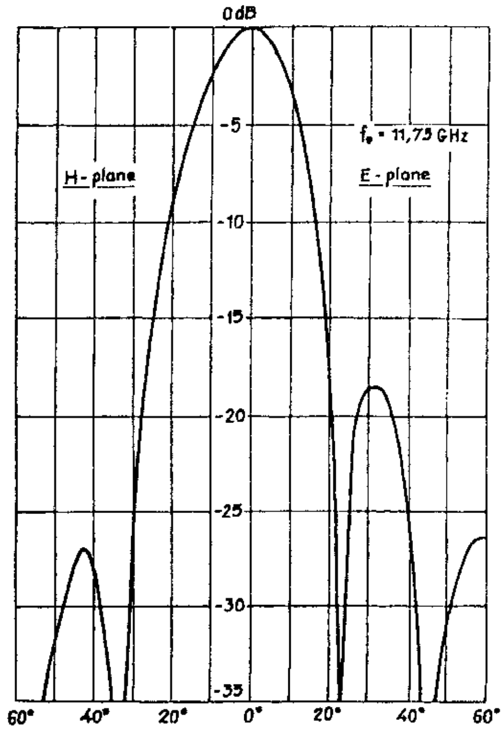

Fig.5
Radiation patterns of the conical horn (calculated as a waveguide)

The polar radiation pattern for the TM_{11} mode is given as follows:

$$E_\theta^{TM}=-\frac{kak_c^{TM}}{2R}\left(\frac{\beta_{TM}}{k}+\cos\theta\right)\cdot$$
$$\cdot\frac{J_1'(k_c^{TM}a)}{1-\left(\frac{k_c^{TM}}{k\sin\theta}\right)^2}\cdot\frac{J_1(ka\sin\theta)}{\sin\theta}\sin\Phi e^{-jkR} \tag{9}$$

where $k_c^{TM}=\sqrt{k^2-\beta_{TM}^2}$ is transverse wavenumber for the TM_{11} mode. From the comparison of (7) and (9), by eliminating constants and assuming that $\cos\theta$ is unity

$$E_\theta^{TE}\approx\sin\Phi\cdot\frac{J_1(u)}{u} \tag{10}$$

and

$$E_\theta^{TM}\approx\left[\frac{1}{1-\left(\frac{k_c^{TM}a}{u}\right)^2}\right]\cdot\sin\Phi\cdot\frac{J_1(u)}{u} \tag{11}$$

where $u=ka\sin\theta$. For large u , the bracketed factor in (11) becomes very close to unity, allowing the possibility of sidelobe cancellation. In order to predict the performance of the dual-mode conical horn in the electric plane, (7) and (9) may be simplified and combined in an approximate form [2] as

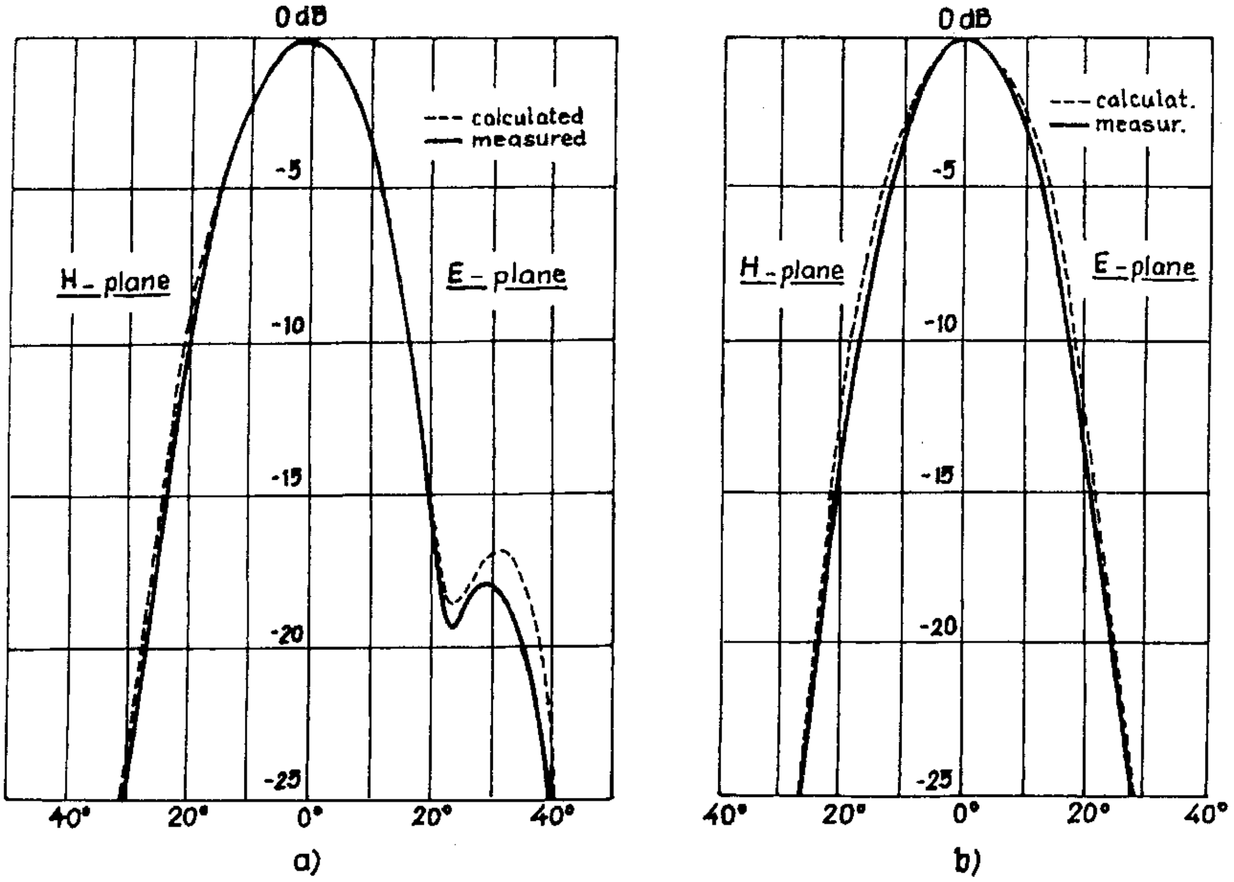

Fig.6
Calculated and measured radiation patterns
a) unloaded horn
b) dielectric - loaded horn ($\varepsilon_r = 2{,}1$; $d = 22$ mm ; $l = 127$ mm)

$$E_{\theta_T} \approx \left[1 - \frac{\varepsilon}{1 - \left(\frac{k_c^{TM} a}{u} \right)^2} \right] \cdot \frac{J_1(u)}{u} \tag{12}$$

where ε is arbitrary constant defining the relative power in the TE_{11} and TM_{11} modes. For example, the value of $\varepsilon = 0{,}653$ will equalize the E - and H - plane half-power beamwidths and make the phase centers coincident.

5. Experimental results

The purpose of experiments has been to verify some parameters of the dielectric-loaded horn antenna such as the radiation patterns in the E - and H - plane, and the impedance matching (VSWR) at the waveguide-horn junction. The experiments were performed at the Radioelectronics Department of EF STU. Because the laboratory conditions did not satisfy all the requirements on the measuremed space for microwave antennas, the measurement of a radiation patterns has been realized only to the level of -25 dB. For the angles $\theta > 50^o$, a considerable influence of reflections occured and the measured results were not reliable.

The basic parameters of a conical horn are according to Section 3 defined. For the dual-mode conical horn operating in the 11,5 - 12,5 GHz band with the dielectric layer location according to Fig.4, these parameters are as follows:

- aperture - conversion point distance $l = 127$ mm,
- length of layer along of the horn wall $d = 22$ mm.

For calculation of the radiation patterns, the relationships (7) and (8) can be used because the aperture diameter of the conical horn is $D = 3{,}03\ \lambda_0$, where λ_0 is wavelength at f_0=11,75 GHz. The radiation patterns of the unloaded horn in the E- and H- planes are shown in Fig.6a). Theoretical radiation patterns are calculated assuming a quadratic phase distribution across the aperture [5].

In Fig. 6b measured radiation patterns of a dielectric-loaded conical horn operating at the frequency $f_0 = 11{,}75$ GHz are plotted.

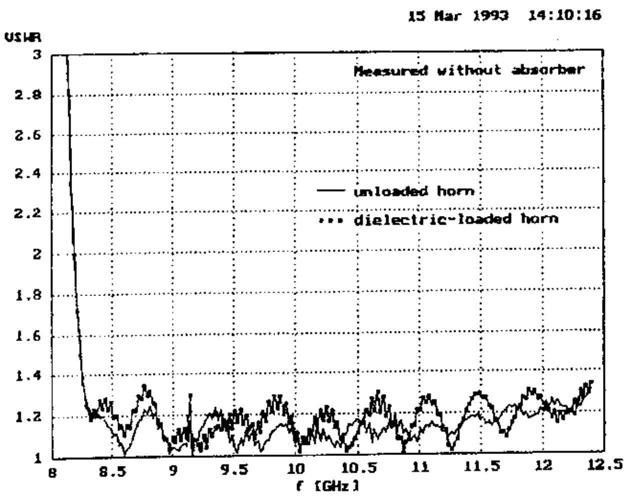

Fig.7
VSWR against frequency

As follows from the measured radiation patterns of the dielectric-loaded horn (Fig.6b), the main beam is completely symmetrical to the -25 dB level and the sidelobes are extremely low in the E- plane. Fig.6a shows the patterns for the same horn without the dielectric layer. Sidelobe levels are as high as -17 dB in the E- plane and the beamwidth difference in E- and H- planes at the -10 dB level is about 30 percent in this case.

It is well known that radiation of the feed its also dependent on impedance matching at the waveguide-horn junction.

Fig.7 shows the measured frquency dependence of VSWR in the X- band using six-port reflectometer [7].

It is seen that the impedance match about the center frequency of the unloaded horn is very good (VSWR≈1,2). In the case of the dielectric-loaded horn, the value of VSWR≈1,3 has been measured in the 11,5 - 12,5 GHz band. It is necessary to note that at realization of the feed the question of impedance matching was not especially investigated and therefore is a realistic assumption that the impedance matching can be improved, e.g. by adaptation of the dielectric layer.

6. Conclusions

One of the possibilities of higher mode generation, a dielectric-loaded horn, has been investigated. Such conical horn with small flare angle radiates a rotationally symmetric beam and has extremely low sidelobes over a bandwidth of more than 20 percent. It is necessary to note that since TM_{11} mode does not radiate axially, the dual-mode has less axial gain than a dominant-mode conical horn with the same aperture size; however, we are more concerned with pattern circularity and sidelobe performance. This horn antenna can be used as a primary feed for reflector-type antennas, especially in Cassegrainian feed systems. It is structurally simpler than corrugated horn antennas and can be used at higher frequencies. Also, manufacture of these horns in comparison with the corrugated feed is simple and inexpensive.

7. Acknowledgment

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8. References

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