LOW LOSS DIELECTRIC WAVEGUIDES

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Introduction

The history of dielectric waveguides begins back in 1910 with the publication of a theoretical paper by Hondros and Debye[1], who gave a mathematical treatment of transverse magnetic mode propagation in lossless dielectric guide. In the 1930's Southworth[2] began experimental work on these modes while Carson, Mead, and Schelkunoff[3] developed a general theory which showed the existence of TE, TM, and hybrid HE modes. During World War II, dielectric rod antennas came into use.[9] However, dielectric waveguides as transmission lines were considered impractical at that time when the shortest wavelengths in use were several centimeters long. The size of dielectric required at these long wavelengths, and the problems of support, radiation, and crosstalk, appeared to be serious drawbacks to the practical utilization of these guides. Furthermore, there was no great need for dielectric guides, since dominant-mode metallic guides had sufficiently low loss while flexibility could readily be obtained by corrugated guides or by coaxial lines.

More recently, with the advent of wavelengths of one centimeter and shorter, there is renewed interest in the low loss and flexibility possibilities of dielectric waveguide transmission. Thus, C. H. Chandler and W. M. Elsasser[4] of R.C.A. have studied the attenuation of circular dielectric waveguides while a group in the Microwave Laboratory of Northwestern University[5] has conducted a more detailed investigation of circular dielectric rod and tube waveguides and has obtained quantitative equations for the fields inside and outside these guides. Experimental and theoretical study of attenuation in these guides was also conducted by this group. A. G. Fox[6] of the Bell Telephone Laboratories has also investigated dielectric waveguide transmission but has concentrated on using them to replace metallic waveguides in bench setups at millimeter wavelengths. This work has resulted in some beautifully simple flexible waveguides, directional couplers and hybrids. This paper will describe some work done at the Bell Telephone Laboratories on low loss, dielectric waveguides suitable for moderate distance transmission.

Dielectric Waveguide Modes

The theory of dielectric waveguide modes is discussed in references 3 and 5, so that only some general remarks will be made here. By a waveguide mode, one generally means a particular electromagnetic field distribution which varies exponentially in the direction of propagation, as $e^{-\gamma z}$ where γ, the propagation constant, can be real, imaginary, or complex. In the case of a hollow metal waveguide, an infinite number of modes can exist at all frequencies, these modes propagating above cutoff (γ is imaginary) and attenuating below cut-off (γ is real). This set of modes in a metal waveguide is complete so that any arbitrary field configuration can be expressed as a sum of the possible modes.

For lossless dielectric waveguides, R.B. Adler[7] has shown that the propagation constant γ can never be real but must be imaginary, i.e., $\gamma = j\beta$. This means that no real cut-off in the ordinary metallic waveguide sense can occur, but it does not mean that all modes can propagate at all frequencies. It merely means that some modes simply cease to exist below a certain critical frequency. At a very high frequency where the waveguide is many wavelengths in diameter, the propagation constant $j\beta$ approaches $j\omega\sqrt{\varepsilon_1\mu_0}$ where ε_1 is the waveguide dielectric constant. This seems reasonable since at these high frequencies the wave energy is confined almost entirely inside the dielectric. As the frequency decreases, the propagation constant decreases until a critical frequency is reached where $j\beta = j\omega\sqrt{\varepsilon_0\mu_0}$ = free space propagation constant. Below this frequency the dielectric no longer guides the wave and the mode ceases to exist, unlike the metallic waveguide modes where below cutoff the propagation constant becomes real. Therefore, "cutoff" seems to be a poor term to apply to this critical frequency of dielectric waveguide modes. Adler[7] has suggested the term "divergence frequency" since the wave diverges from the dielectric instead of being guided by it at this frequency. From the above it is evident that at any given frequency only a finite number of modes can exist. Therefore, these modes cannot form a complete set since an arbitrary field configuration cannot be expressed as a sum of these modes but must be expressed as the sum of the propagating modes and radiating terms.

Most of the modes in dielectric waveguides must have longitudinal components of both E and H, and these modes are usually designated as "hybrid" modes and symbolized by the Northwestern University group by HE_{nm} if the field in a cross-section resembles that of an H (TE) wave or EH_{nm} if it resembles that of an E (TM) wave. It can be shown that transverse electric or transverse magnetic modes can be propagated only if the fields have axial symmetry.

The lowest order transverse electric, TE_{01}, and transverse magnetic mode, TM_{01}, can exist on a polystyrene rod only if the rod is greater than

0.626 wavelengths in diameter. Near this diameter-to-wavelength ratio, almost all of the wave energy is in the space surrounding the guide so that the guide wavelength is very nearly the same as the free space wavelength. However, as the diameter-to-wavelength ratio increases, the guide wavelength decreases rapidly and approaches the wavelength in an infinite medium of the dielectric at large diameters as seen in Figure 1. One can also state that the loss would increase (Figure 2) as the guide wavelength decreases since both variations depend upon the amount of the field energy inside the dielectric.

Of the hybrid modes, the HE_{11} mode has no "divergence" frequency and can be propagated at all frequencies regardless of diameter. Of course, at very low frequencies, this mode becomes essentially a free space transverse electromagnetic wave with practically no loss and no guiding action by the dielectric. As the diameter-to-wavelength ratio increases, the guiding action improves and the guide wavelength deviates appreciably from the free space wavelength, as seen in Figure 1. A field plot of the HE_{11} mode is shown in Figure 3, and one can note that this mode is very similar to the dominant TE_{11} mode in circular waveguide. Figure 2 is a curve of loss as a function of guide diameter as calculated by the Northwestern University[5] and R.C.A. groups.[4]

Choice of Mode

A dielectric waveguide mode which is best suited for microwave transmission should be easy to launch, should have low loss, and should be as immune as possible to mode conversion or radiation due to the necessary manufacturing tolerances of the guide.

Let us first consider the launching problem. Since the HE_{11} mode has a field pattern which is very similar to the dominant TE metallic waveguide mode, launching can be very simply accomplished by merely inserting the dielectric in a dominant mode metal guide properly flared as shown in Figure 4. All other modes would require mode transducers for launching.

As to loss, it can be seen from Figure 2 that the HE_{11} mode has low loss over a wider range of diameters than the loss for the transverse modes which rises very rapidly from zero to a rather high value, so that very slight diameter changes could cause very large changes in loss. Thus, the HE_{11} mode permits wider dimensional tolerances and so is to be preferred.

The HE_{11} mode is also to be preferred from the mode conversion point of view. If the dielectric diameter-to-wavelength ratio is low (below .626 for polystyrene), no mode conversion can take place since only the HE_{11} mode can exist on the guide. Guide discontinuities will, instead, cause wave radiation. This radiation is, however, not as serious a problem in transmission as mode conversion with its interference potentialities would be.

We therefore see that the hybrid HE_{11} mode is superior for microwave transmission purposes to all other modes.

Guide Configuration

One of the first problems to be investigated was the particular guide configuration, (whether rod or tube, of circular or rectangular cross-section) which would give the lowest losses and require the lowest tolerances on uniformity while still confining the energy within a given area.

The relative merits of the rod and tube forms of the dielectric guide can be obtained theoretically from the equations given by the Northwestern University Group. With the aid of S. P. Morgan of the Laboratories, calculations were made of the relative power flow in various regions for a particular rod and a particular tube whose losses were nearly equal. The results indicate that the rod confines the field better than the tube does for the given dimensions.

On the other hand, the guide wavelength is a much more slowly varying function of diameter for the tube than for the rod so that dimensional tolerances would not be as strict for the tube. However, this advantage was not considered sufficient to warrant the added manufacturing difficulties involved in tube fabrication.

The problem of the guide cross-section was not treated theoretically because of the very great difficulties involved in solving the dielectric waveguide problem for other than circular cross-sections. However, experiments with circular guides by A. G. Fox had already shown that these were unsuitable for transmission purposes because internal strains, dimensional non-uniformity, and bends caused the HE_{11} dipole mode to change polarization. It was therefore decided to use rectangular or oval cross-section guides. Depolarization effects are minimized with these cross-sections because the guide wavelengths differ for the two perpendicular axes of the cross-section. Our work thus complements the work done at other laboratories on the mathematically simpler circular rod waveguide.

Attenuation Measurements at 24,000 MC

The theory of circular dielectric rod waveguide attenuation has been discussed by Elsasser[4] and by the Northwestern University group[5] for polystyrene with results shown in Figure 2, but no theoretical study has been made for attenuation in rectangular dielectric guides because of its extreme complexity. An experimental study of this problem was therefore undertaken. It was expected that the attenuation of a rectangular guide with the E vector along the long dimension would be equal to the attenuation of a circular guide of diameter somewhat smaller than the long rectangular dimension. Similarly, with the E vector along the short dimension, the loss was expected to be equal to the loss of a circular guide of diameter somewhat larger than the short dimension.

The measurements were made using two different methods. The first involved the straightforward scheme of directly measuring the loss of a guide sufficiently long to give results of fair accuracy. This was rather difficult to do because long lengths of uniform cross section are not easy to obtain. Furthermore, long lengths of line are unwieldly and require a long unobstructed path. However, several long length measurements were made both on samples cut from sheet stock and then heat welded to form a suitable length line, and also on lengths extruded by a commercial extruding firm.

The results of the long line measurements are shown in Figure 5. The line constructed from sheet stock was rectangular in shape with dimensions of 0.095" x .156". The loss was measured at 24,000 mc for various lengths of line, resulting in an average loss measurement of 0.05 db/ft. for the electric field parallel to the long dimension. The radius of field extent was measured rather roughly so that no great quantitative accuracy is claimed for it. However, the measurement does indicate that large metal or absorbing plates could be brought to within 1 1/2" of the guide with no noticeable effect (less than 1%) on the transmission. One could also rotate the polarization of the receiving horn a full 360° with respect to the sending horn in a 35 ft. line without affecting the received output. This line could also take a 45 ft. radius of curvature with less than 1% effect on output.

The commercially manufactured line was oval in shape and had dimensions of 0.086" x 0.155" with a variation of ±.005". Because of the smaller dimensions of the extruded line and because its cross-section was oval rather than rectangular, the field extended over an 8" diameter rather than the three-inch diameter obtained with line made from sheet stock. For the same reason, the extruded line was also expected to have a substantially lower loss than the hand-made line. It was therefore surprising to measure a loss of 0.05 db/ft. for this line as well.

The only reasonable explanation for this high loss is that the extruded polystyrene had an inherently higher loss tangent due perhaps to impurities introduced by the extrusion machine. Measurements confirmed our suspicions and showed that at 3,000 mc the sheet stock had a loss tangent of 0.0006 while the extruded material had a loss tangent of 0.0022. It was therefore evident that dielectric waveguide measurements made with extruded polystyrene would be pessimistic. Steps were therefore taken to obtain a better grade of material from another source. However, this new material arrived after the present 24,000 mc measurements were terminated.

The second method of measuring dielectric waveguide loss involved a resonant line technique similar to that used by C. H. Chandler[4] and W. C. Jakes.[5] In this method, the dielectric waveguide is placed between two parallel plane reflectors, thus forming a resonator which effectively multiplies the length of the guide. Transmission through the resonator takes place when it is a multiple number of half wavelengths long. By measuring the Q of the transmission peaks as a function of length of line, one has sufficient information to calculate the dielectric waveguide attenuation.

Using this resonator technique, loss measurements were made on the commercially extruded polystyrene guide. With the electric vector polarized along the 0.155" dimension, the loss was measured to be 0.049 db/ft., which is in good agreement with the long line measurements. The field extent as measured in the resonator also agreed with the long line measurement. With the electric vector along the 0.086" dimension, the field was confined to a diameter of approximately 14 inches, while the loss dropped to 0.025 db/ft.

Attenuation Measurements at 48,000 MC

The attenuation measurements at 48 kmc were taken in two ways: The first was the long line technique discussed earlier. The second method made use of a movable directional coupler that makes it possible to take measurements at any point along the line. The use of the directional coupler, however, presented various difficulties. The line supplied by the manufacturer, with a cross section nominally 0.056" x 0.142", showed a periodic dimensional variation. These variations, by changing the coupling factor, produced an oscillatory component in the power measured along the transmission line. In order to obtain uniform dimensions and a smaller cross section, the polystyrene was accurately sized. However, the oscillatory component persisted, and it was necessary to use the average of a number of measurements to obtain the transmission loss. We have attributed the remaining oscillations to variations in the dielectric constant which caused variations in the coupling coefficient. The changes in the dielectric constant can be correlated with the dimensional variations that were present in the unsized polystyrene.

The loss of a 100' of 0.056" x 0.142" polystyrene line supported every 6' by nylon thread varies from 24 to 30 db/100 ft. with E perpendicular to the large dimensions of the guide. With E along the large dimension, the loss measured varies from 94 to 120 db/100 ft. The larger values of attenuation were obtained when the relative humidity was in the vicinity of 100%. The alignment of the line was not critical, even with E perpendicular to the large dimension of the guide. Displacing the center of a 100' line by 1' did not give an observable increase in attenuation. However, displacing the center of a 2' section by 1" resulted in an added loss of 0.5 db. Specifying the effect of misalignment in a unique way is somewhat difficult. The radiation loss due to uniform circular bends is of little practical interest, since accidental misalignment does not produce uniform bends. We have given here the losses caused by displacing the guide supports. It should be borne in mind, however, that these losses are influenced by the mechanical properties of the line, since these properties determine the sharpness of the bend for a given displacement of the supports.

The field extent for polystyrene line sized to rectangular cross section of 0.038" x 0.114" was experimentally found to be about 1.5" in radius. The loss of a 100' of this dielectric waveguide, supported every 6' by nylon thread, is 4.5 db/100 ft. with E along the small dimension of the guide. All the values given here are believed to be correct within ± 0.2 db. Introduction of a 360° twist spaced over 12' resulted in a loss of approximately 1 db, but the twist did not produce appreciably any cross-polarization (more than 20 db down).

The last waveguide considered was polystyrene, 0.032" x 0.096" in cross section. A 106' section of this guide supported every 4' by nylon thread gave a transmission loss of about 0.7 db/100 ft. The alignment of the line was quite critical. The displacement of one of the supporting threads by 1" resulted in an additional loss of approximately 2 db. Supporting the line only every 12' increased the loss to $\frac{1.2 \text{ db}}{100 \text{ ft}}$. Introduction of a 90° twist spaced over 12' resulted in a loss of 0.5 db. A 180° twist in 12' produced a cross-polarization component which was approximately 20 db down. Displacement of the line did not produce any observable cross-polarization.

The experimental results are summarized in Figure 7.

Launching

As stated previously, the HE_{11} mode can be launched on a dielectric waveguide by inserting the tapered end of the waveguide inside a dominant-mode rectangular metal guide with attached horn as shown in Figure 4. A number of experiments were performed to determine the optimum horn dimensions for low loss launching. Qualitatively, it can be stated that both the length and flare angle of the horn are important and must be optimized. For the .095" x .156" guide with the E vector along the long dimension, the best results were obtained with a 10" long horn and a 20° flare angle. The launching loss for this horn was about 0.75 db/horn.

As the dielectric cross section becomes smaller and the field outside the dielectric becomes larger, launching becomes relatively more difficult. This was particularly true in the 48,000 mc launching experiments. Thus, for the .056" x .142" guide having a radius of field extent of about 0.4 inches, a conical horn with an axial length of 5" and a diameter of 1 3/4" gave a launching loss of 1.0 db. The same horn had a launching loss of 5.1 db for the small 0.032" x 0.096" guide. In order to reduce this loss to 1.5 db for the latter guide, a 21" long horn having two flare angles with a 4" diameter opening was required. In order to further reduce this loss, various schemes using lenses and tapered dielectric waveguides were tried without success.

Guide Shield

A dielectric waveguide requires an electrical and mechanical shield to protect it from electrical crosstalk and from rain, snow, etc., as well as to permit the guide to operate in a non-absorbing dry atmosphere. However, this shield need not meet the very close mechanical tolerances which multimode metallic waveguides require.

Shielding experiments were performed using the resonator technique. A metal shield was found to result in many spurious resonances due to coupling between the hybrid dielectric mode and the metal guide modes. It is therefore felt that metallic shields will be unsatisfactory and will result in mode cross-couplings.

The best shielding will therefore be obtained with a lossy tube of large diameter so as not to intersect any of the energy surrounding the dielectric. Since no large diameter commercial tubes were available, 1/2" plywood was tried and found satisfactory.

Guide Supports

Tests were conducted, using both the resonator and the long line techniques, to determine possible means of supporting dielectric waveguides. Thin nylon threads were found quite suitable. Thin polyfoam sheets were also tried and found satisfactory only if they were symmetrical about a plane perpendicular to the electric vector and about a plane perpendicular to the magnetic vector. These supports were 1/4" thick, 10" square and placed at ten-inch intervals along a 150 ft. length of .095" x .156" polystyrene line without perceptibly increasing the transmission loss. However, asymmetrical polyfoam supports produced large losses due to radiation.

The support problem for vertical runs is not solved by the polyfoam sheets and further work is required. One possible solution is to insert a wire in the center of the dielectric guide in order to add strength to the dielectric while only slightly perturbing the hybrid mode. Tests made at 24,000 mc showed that a .025" diameter wire center in a .146" diameter polyethylene guide does not add much to the electrical loss while considerably improving on the somewhat poor mechanical properties of dielectric waveguides. However, where mode purity is important, this wire-dielectric guide is as yet impractical since the wire permits the propagation of a closely confined, high loss, TM mode of the Goubau type. This latter objection may perhaps be eliminated by using a center wire of high resistivity.

Another possible solution to the support problem is the dielectric image guide. Since the field distribution of the HE_{11} mode possesses a plane of symmetry, one can split the dielectric rod in two and use an image plane as shown in Figure 6. Of course, this image plane adds copper losses to the normally present dielectric losses of a dielectric guide. However, since the field intensities are relatively low, conduction current densities, and therefore copper losses, will be low too. D. D. King[8] has published some experimental results on this type of guide.

Conclusions

For short distance transmission on bench setups (at frequencies above 24 kmc) where very low loss is a comparatively unimportant factor, the flexibility, ease of manufacture, and low cost of dielectric waveguides, have already proven to be of very great value by the work of A. G. Fox.

For moderate distance transmission, such as up to an antenna a few hundred feet from the signal source, one may frequently be willing to sacrifice transmission efficiency in order to obtain an inexpensive and reliable transmission line. For this application, dielectric waveguides may be attractive if one can effectively solve the problem of supporting the guide vertically. The dielectric image guide appears to be particularly suitable for this application.

For long distance transmission, one could justify the use of dielectric guides if they could compete with the circular electric TE_{01} mode transmission in circular metallic waveguide. The latter can provide low-loss transmission in a relatively smaller space than the dielectric guide can. Although further work on dielectric waveguides would be required before a quantitative comparison could be made of these two low-loss long-distance transmission means, it does appear that the circular electric mode in metallic waveguides is superior for this service.

We wish to express our appreciation to Mr. A. G. Fox for the very many helpful and stimulating discussions which materially aided the progress of this investigation.

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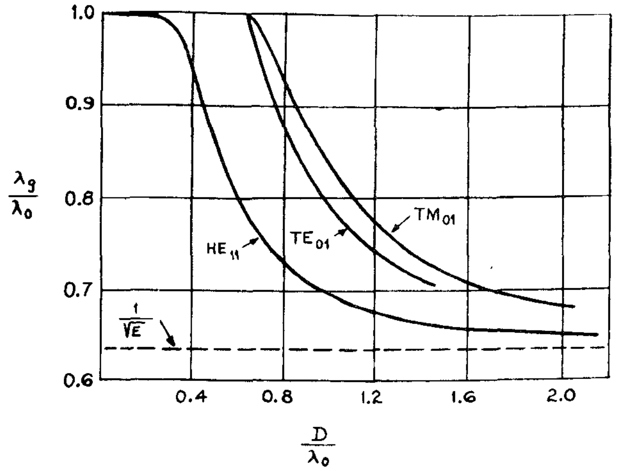
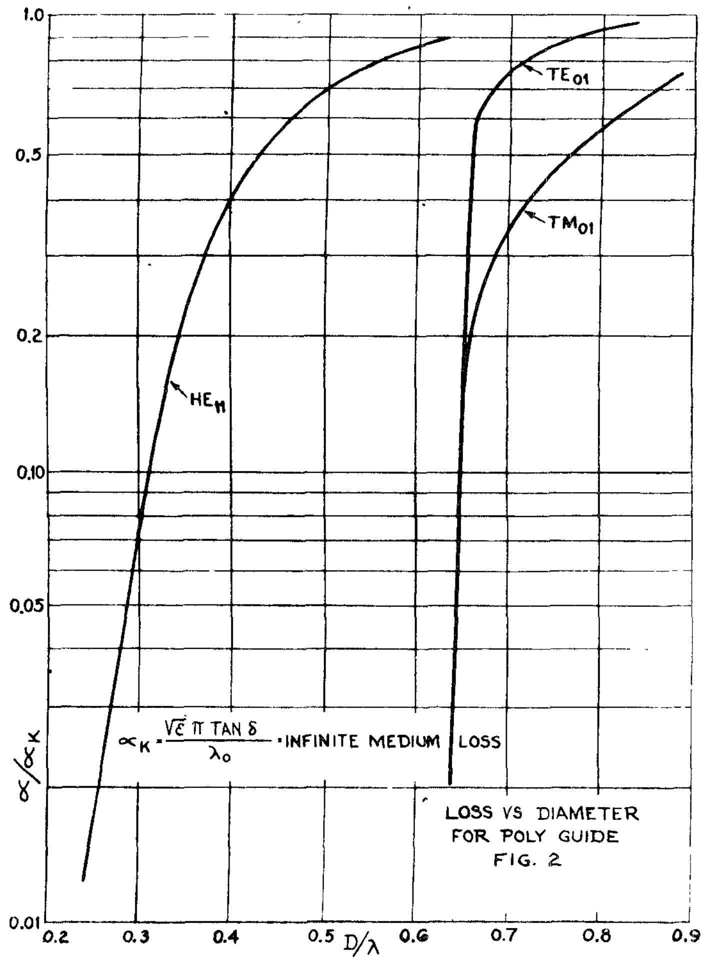


FIG. 1

GUIDE WAVELENGTH VS. DIAMETER FOR POLYSTYRENE WAVEGUIDE



LOSS VS DIAMETER FOR POLY GUIDE

FIG. 2

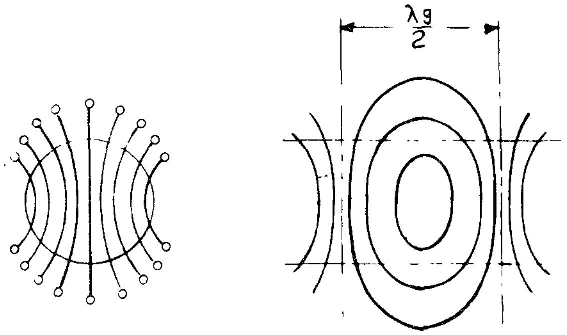


FIG. 3

APPROXIMATE E FIELD CONFIGURATION OF THE HE_{11} MODE ON A DIELECTRIC ROD WAVEGUIDE

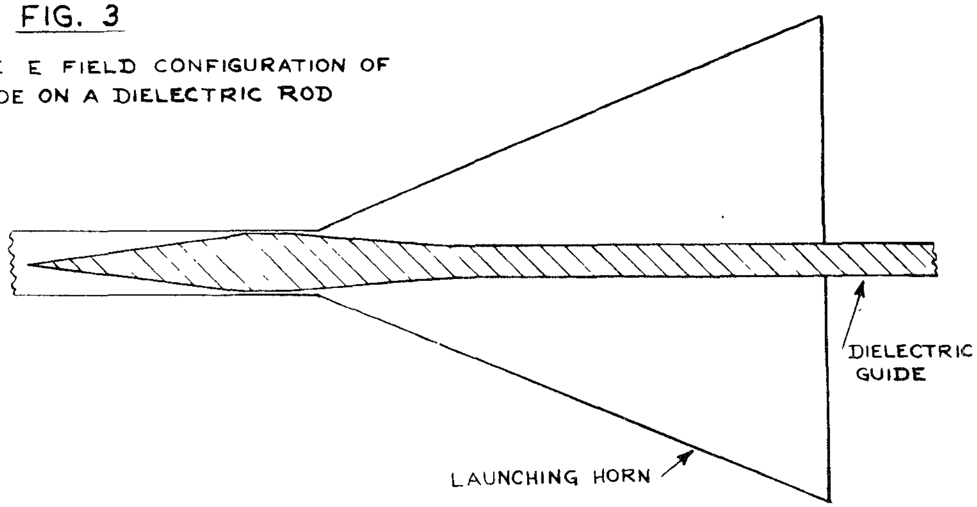


FIG. 4

LAUNCHING OF HE_{11} MODE

MATERIAL POLYSTYRENE	DIMENSIONS INCHES	E DIRECTION	RADIUS OF FIELD EXTENT (INCHES)	LOSS db/FT
SHEET STOCK	.095 x .156	↑	1.5	.05
EXTRUDED	.086 x .155	↑	4	.05
EXTRUDED	.086 x .155	←	7	.025

FIG. 5

ATTENUATION OF DIELECTRIC WAVEGUIDE AT 24,000 M.C.

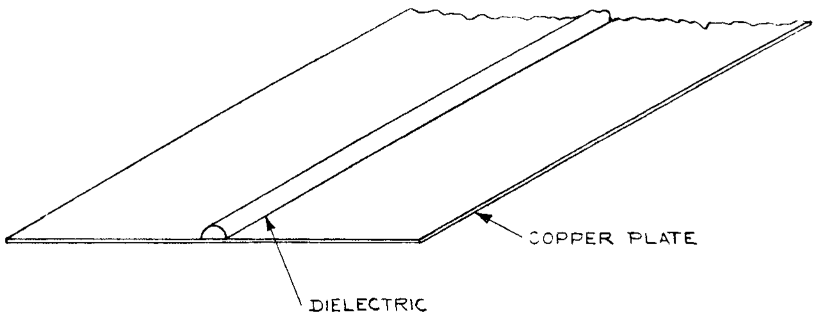


FIG. 6

IMAGE LINE

GUIDE DIMENSIONS (INCHES)	E DIRECTION	RADIUS OF FIELD EXTENT (INCHES)	LOSS db/FT
.056 x .142	←	.4	1.0
.056 x .142	↑	.8	.27
.038 x .114	↑	1.5	.045
.032 x .096	↑	3	.007

FIG. 7

ATTENUATION OF DIELECTRIC WAVEGUIDE AT 48 KMC