The Attenuation of the Holmdel Helix Waveguide in the 100–125-Kmc Band*

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The attenuation of the Holmdel, N. J., Bell Telephone Laboratories two-inch diameter helix waveguide operating in the circular electric mode has been measured in the 100–125-kmc band. With these measurements the helix waveguide attenuation is now known from 33 kmc to 125 kmc. Above 100 kmc the loss increases with frequency, as contrasted to all previous lower-frequency measurements, which show the loss decreasing with increasing frequency. The minimum loss of 2 db/mile occurs around 90 kmc. The loss is below 3 db/mile from 40 kmc to 116 kmc. A loss peak observed at 122 kmc is believed due to the method of supporting the sections of the waveguide measured. An analysis of the loss peak is presented which indicates that this loss peak can be avoided by suitably supporting a helix installation.

I. INTRODUCTION

The advantages of overmoded circular waveguide using the TE_{01} mode for long-distance transmission in the millimeter-wave region have long been recognized.[1] The added advantage of the circular helix waveguide in giving spurious mode suppression has also been considered.[2] The propagation characteristics of the Holmdel, N. J., Bell Laboratories two-inch diameter helix waveguide, which is made to very precise tolerances, have been investigated extensively, and its attenuation has previously been measured from 33 kmc to 90 kmc.[3] The work reported on here extends these measurements to 125 kmc.

Over the previously measured band the attenuation decreases with increasing frequency and falls below 2 db/mile at 90 kmc. It was previously not known how high in frequency this decreasing trend would continue nor to how low the attenuation would fall. The measurements

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in the 100–125-kmc band show that the minimum has been passed and that the losses in this band increase with frequency.

As far as is known, these are the only relatively precise measurements which have been reported on low-loss millimeter waveguide in the range from 100 to 125 kmc. They extend the known communications bandwidth of a practical waveguide by about 30 kmc.

II. MEASURING METHOD

The measuring technique used was the single-oscillator shuttle-pulse method described by others.[3]

The rectangular waveguide components were of the RG 138/U size, and the circular waveguide components were designed for use in the 120-kmc band. The millimeter-wave mixer diodes used were developed by Sharpless.[4] The mode transducer for exciting the circular electric mode is a two-stage transducer. The rectangular TE_{01} is converted to rectangular TE_{02} and then to circular TE_{01}.[5,6]

The waveguide being measured was filled with dry nitrogen at a positive pressure to avoid losses due to gas absorption.

III. ATTENUATION MEASUREMENTS

The measured attenuation of the 2-inch helix waveguide as a function of frequency is shown in Fig. 1. The attenuation from 33 to 90 kmc was

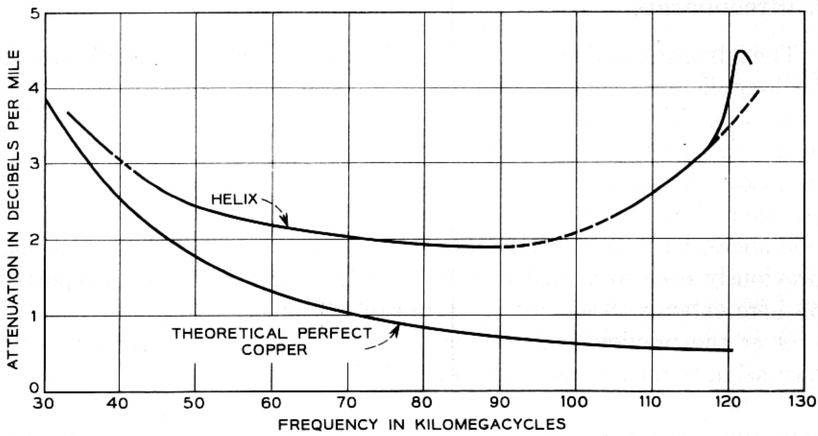

Fig. 1 — Measured attenuation of circular electric mode in 2-inch diameter helix waveguide.

measured by King and Mandeville.[3] The dashed curve from 90 to 105 kmc and around 40 kmc indicates that no measured data are available in these ranges. The dashed curve under the loss peak at 122 kmc indicates the expected curve in the absence of the loss peak. Also shown is the theoretical loss for perfect copper waveguide.

The measurements in the 120-kmc band were taken on several different sections of helix to give an indication of the performance of typical helix. The accuracy is ± 0.1 db/mile.

The new data show the losses increasing with frequency, with a minimum loss of 2 db/mile around 90 kmc. The loss of the 2-inch helix waveguide is less than 3 db/mile over a band from 40 kmc to 116 kmc.

The theoretical loss for the TE_{01} mode in perfect copper pipe continues to decrease with increasing frequency. The fact that the helix loss increases above 100 kmc can probably be attributed to imperfections in the helix. These imperfections, such as changes in diameter, ellipticity, and random deviations of the axis from a straight line, cause mode conversion and hence increased loss. Calculations indicate that the loss of the TE_{01} mode itself in the Holmdel helix is the same as in solid copper pipe even at the highest frequencies used here.

The additional loss peak at 122 kmc is believed not a property of the helix itself and is considered below.

IV. ANALYSIS OF LOSS PEAK

A peak in the loss curve is clearly shown in Fig. 1 at 122 kmc. The analysis presented in this section indicates that the loss peak is probably due to the way in which the helix was supported. This means that in a helix waveguide installation this loss peak can be avoided by proper support methods. The loss is believed caused by power being converted to the TE_{11} mode or possibly the TE_{12} mode and hence lost in the lossy lining of the guide. The TE_{11} and TE_{12} conversion is caused by the flexing of the waveguide between the support points due to its own weight. This is the serpentine bend effect described by Unger.[7] It is believed that this is the first time this effect has been observed in helix waveguide.

The measured waveguide was supported at 15-foot intervals and flexed ≈ 0.040 inch between support points. At a frequency where the beat wavelength between the TE_{01} and some spurious mode reaches 15 feet or some submultiple of 15 feet, the coupling to the spurious mode will be greatly increased.

From the calculations of Unger[8] and Miller[9] for helix waveguide, Fig. 2 shows a plot of beat wavelength vs frequency for several spurious modes. At 122 kmc the beat wavelength for the TE_{11} mode is 7.5 feet, which is one-half the nominal 15-foot support interval. Hence a loss peak due to TE_{11} mode conversion is to be expected at 122 kmc.

At 122 kmc the beat wavelength for the TE_{12} mode is 4.7 feet, which would correspond to one-third of a support spacing slightly less than 15 feet. Since the actual support spacing varied somewhat around 15 feet, it may be possible that the TE_{12} also contributes to the loss peak.

To see if this explanation of the loss peak is reasonable, a calculation of the expected magnitude of the TE_{11} loss peak in helix can be made from the analysis for copper waveguide by Rowe and Warters[10] and by Unger.[7] Although the following calculation is for the TE_{11} mode, a similar calculation can be made for the TE_{12} mode.

Rowe and Warters show that the shapes of these mode conversion loss peaks vary with frequency, f, as

$$\left[\frac{\sin \pi \frac{L}{B_0 f_0}(f_0 - f)}{\pi \frac{L}{B_0 f_0}(f_0 - f)}\right]^2$$

for the case of no differential attenuation between the TE_{01} and the spurious mode. Here L is the distance over which the energy is fed in phase into the spurious mode, f_0 is the center frequency of the loss peak, and B_0 is the beat wavelength at f_0. The longer the interaction distance, the narrower and higher is the loss peak.

When differential loss is introduced between the TE_{01} and the spurious mode, as in the helix case, the first-order effect is to reduce the interaction length. This causes a lower and wider loss peak, but to first order the area under the curve remains the same as for the case of no differential loss. The expected area under the loss curve for helix can therefore be calculated from the theory for copper waveguide.

From equations (171) and (178) of Ref. 10, assuming a $[(\sin X)/X]^2$ shape, the area of the loss peak is expected to be:

$$\text{area} = 2.06 \times 10^4 B_0 f_0 \, | c_n |^2 (\text{db/mile}) \text{ kmc} \tag{1}$$

where

f_0 = frequency at the peak of the loss curve in kmc

B_0 = beat wavelength in feet of the spurious mode at frequency f_0

c_n = Fourier coefficient in feet^{-1} of the curvature mode coupling coefficient corresponding to a spatial wavelength equal to B_0.

For axial bends the curvature mode coupling coefficient, $C(z)$, is inversely proportional to the radius of curvature, $R(z)$, of the bend.

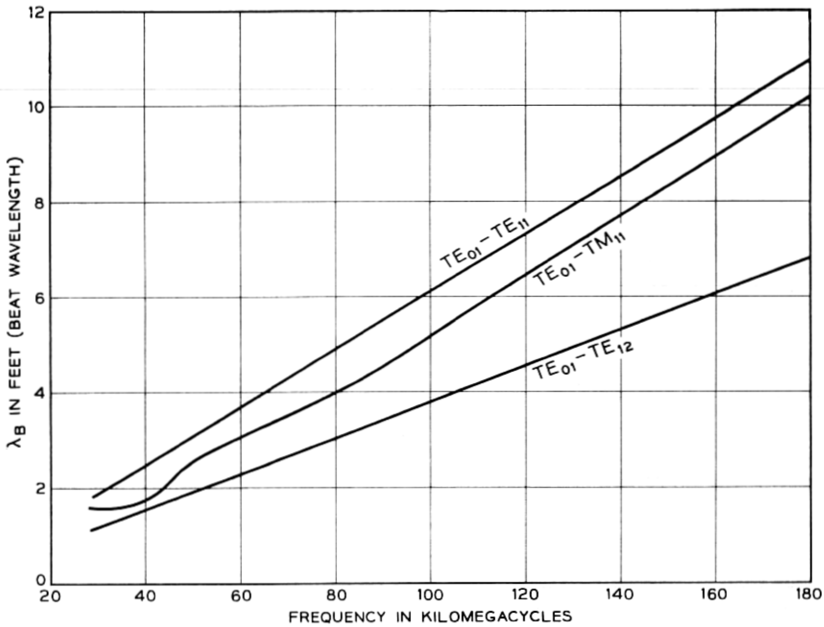

Fig. 2 — Beat wavelength vs frequency for 2-inch diameter helix waveguide.

$$C(z) = C_t/R(z)$$

where C_t is the tilt coupling coefficient for TE_{01} to TE_{11} conversion as computed by Morgan.[11] If the radius of curvature is computed assuming the guide bends from its own weight between the support points, the nth Fourier coefficient of the coupling coefficient is

$$c_n = C_t w L^2/4EI(\pi n)^2 \tag{2}$$

where

w = weight per unit length of the pipe
L = distance between support points
E = Young's modulus for the pipe
I = moment of inertia of the pipe
n = L/B.

Using the appropriate value for 2-inch diameter helix waveguide and $C_t = 12$, $n = 2$, one finds:

$$\text{area} = 3.53 \text{ (db/mile) kmc.}$$

An estimation of the width at the half-height points on the loss hump can be obtained from Young.[12] This assumes that the differential attenuation is relatively large, as is the case in helix:

$$\Delta f = (2\Delta\alpha/\Delta\beta)f_0 \tag{3}$$

where

f_0 = frequency at the peak of the loss curve

$\Delta\alpha$ = differential attenuation = $\alpha(TE_{01}) - \alpha(\text{spurious})$

$\Delta\beta$ = differential propagation constant = $\beta(TE_{01}) - \beta(\text{spurious}) = 2\pi/B_0$.

From the work of Unger[8] and Miller[9] the differential loss between the TE_{01} and TE_{11} in helix at 122 kmc is 8.3×10^{-3} nepers per foot. This gives an expected half-height width at 122 kmc of

$$\Delta f = 2.4 \text{ kmc}.$$

From Fig. 1, if the curve is assumed symmetrically, the area and half-height width of the measured hump can be computed. The area is measured as that above the extrapolated average-loss curve shown in Fig. 1 as a dashed line under the loss peak.

A comparison of the theoretical and measured properties of the loss peak is made in Table I.

The comparison between the measured and the theoretical values is reasonable and indicates that the observed hump is most probably due to mode conversion as discussed. Because of the underground installation it was not physically possible to check this conclusion by varying the support spacing.

It is expected that a similar phenomenon should occur when the beat wavelength is 5 feet, or $\frac{1}{3}$ of the support spacing. For the $TE_{01} - TM_{11}$ beat this occurs at 97 kmc, where good experimental data are not available. For the $TE_{01} - TE_{12}$ beat this occurs at 132 kmc and may contribute to the observed loss peak as mentioned earlier. The TE_{01} –

Table I — Comparison of Observed Loss Peak with Theoretical Loss Peak Assuming $TE_{01} \rightarrow TE_{11}$ Mode Conversion

	Position in Frequency	Area under Loss Peak	Half-Height Width of Loss Peak
Theoretical	122 kmc	$3.53 \frac{\text{db-kmc}}{\text{mile}}$	2.4 kmc
Observed	122 kmc	$3.0 \frac{\text{db-kmc}}{\text{mile}}$	3.0 kmc

TE_{11} beat wavelength is 5 feet at 82 kmc, which falls in a measured range. It is of interest to compute the expected magnitude of the loss peak at 82 kmc to see if the effect is observable.

Using the same appropriate constants as earlier, with $C_t = 8.1$, $n = 3$, the area from (1) is

$$\text{area at 82 kmc} = 0.149 \text{ (db/mile) kmc.}$$

The expected half-height width, using $\Delta\alpha = 3.6 \times 10^{-2}$ nepers per foot, is

$$\Delta f \text{ at 82 kmc} = 4.7 \text{ kmc.}$$

The height of the loss peak above the average curve is then approximately 3×10^{-2} db/mile. This small, wide peak would not be observable in the measurements.

V. SUMMARY

The attenuation of the Holmdel two-inch diameter helix has now been measured from 33 kmc to 125 kmc. Above 100 kmc the losses increase with frequency. This increase is attributed to mode conversion due to random imperfections in the waveguide. The loss is less than 3 db/mile from 40 kmc to 116 kmc.

The loss peak observed at 122 kmc is believed to be not a property of the waveguide itself but of the method of support. It is important therefore in a helix installation to take care in supporting the waveguide so that these loss peaks do not fall in a frequency range where the waveguide is to be used.

VI. ACKNOWLEDGMENTS

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