The Observed 33 to 90 kmc Attenuation of Two-Inch Improved Waveguide

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The TE_{01} losses in long two-inch inside diameter circular waveguide lines were measured over the frequency range of 33 to 90 kmc using shuttle-pulse techniques. Experimental results obtained with two types of waveguide—one solid-wall copper and one helix—are presented. Loss curves for both types are given, along with the theoretical loss curve. Statistical results on TE_{01} loss variations due to mode conversion in the solid wall guide are also given. A new method for making shuttle-pulse loss measurements with a single backward-wave oscillator is described.

I. INTRODUCTION

The conditions favorable for low TE_{01} transmission loss in waveguide occur when the operating frequency is remote from cutoff and many other modes can consequently coexist. Two-inch inside diameter copper pipe can, for example, propagate 80 modes at 33 kmc, nearly 300 modes at 60 kmc, and about 700 modes at 90 kmc. When so many modes can be propagated, the presence of imperfections in the waveguide will introduce coupling between the TE_{01} and other modes. The spurious modes which are excited at such imperfections increase the TE_{01} loss, and a distribution of such imperfections can produce mode conversion-reconversion effects[1,2] which cause the TE_{01} loss to fluctuate in an unpredictable manner with frequency.

Imperfections which occur in a long line can be divided into two categories: joints between sections and imperfections in the pipe itself. Discontinuities at the joint comprise tilt, offset, and change in diameter. The imperfections of the pipe are of a more distributed nature and comprise changes in diameter, ellipticity, and the more or less random deviations of the axis from a straight line. It has been shown by experience that with care both the joints and cross-section tolerances of the pipe can be controlled so that increases in the TE_{01} losses from these sources are quite small. An analytic study and experiments by Rowe and Warters[3] have shown that the variations in axial straightness contribute appreciably to increased losses and fluctuations of the TE_{01} mode. The theory shows that these mode conversion-reconversion effects occur when the period of these variations equals the beat wavelength.* The beat wavelengths of the TE_{01} mode with TE_{12} and with the TE_{11} modes over the 33 to 90 kmc band fall in the 1- to 5-foot range. In a waveguide, when the periods of components of the axial variations relative to a straight line also fall in the 1- to 5-foot range, the resulting interaction causes the average TE_{01} loss to increase and the actual loss to fluctuate with frequency.

It is the purpose of this paper to present the experimental results obtained with two types of waveguide made with very precise tolerances. One of the lines employed conventional solid-copper-wall waveguide, the other was an all-helix waveguide. The measured data cover a 33 to 90 kmc frequency band. A brief description of the measuring technique which was employed for these measurements is included.

II. DESCRIPTION OF LINES

The TE_{01} loss measurements were made on straight two-inch inside diameter lines laid in a straight steel conduit. The individual sections were about 15 feet long and were joined together with special threaded couplings[4] which minimized offset and tilt at the joint. "O" rings between the coupling and the pipe were employed to seal the line. It was important to pump out the line to remove the oxygen and water vapor in order to avoid added losses due to absorption effects.[5] The presence of atmospheric oxygen at standard pressure increases the TE_{01} line loss by a factor of 20 at 60 kmc. The presence of water vapor increases the losses to a lesser extent over the 50 to 90 kmc band, but the increase rises rapidly with frequency above 100 kmc.[6]

The solid-wall waveguide comprised oxygen-free high-conductivity copper of commercial manufacture to very close tolerances. The helix waveguide[7] line (Fig. 1) was constructed in our laboratory by winding No. 37 wire on a precision mandrel. Over the helix winding a layer of glass fibers, coated with conductive material, was wound. This layer provided the necessary loss to attenuate the spurious modes. These elements were bonded together and to the outer steel shell with epoxy resin.

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* The beat wavelength, λ_B, of mode 1 with mode 2 is defined as $1/\lambda_B = (1/\lambda_1) - (1/\lambda_2)$, where λ_1 and λ_2 are the guide wavelengths of the individual modes.

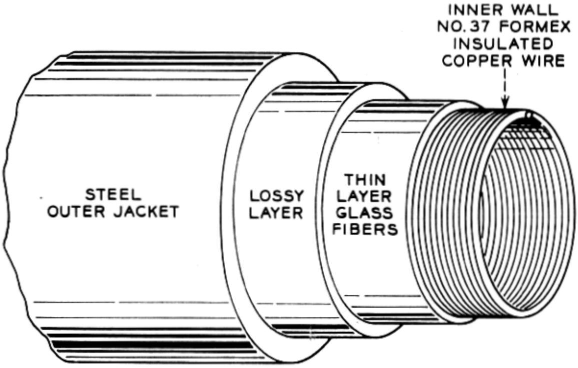

Fig. 1 — Helix waveguide line.

III. MEASURING TECHNIQUE

The TE_{01} losses were measured by the shuttle-pulse method (Fig. 2). This was accomplished by placing an iris at the input and a short at the far end of the section of line to be measured. The iris is a plane traverse metallic mesh with uniformly spaced holes which transmits only a small part of the incident pulse and decouples the measuring equipment from the line without introducing spurious modes. In the measuring equipment the iris was proportioned to transmit approximately 1 per cent of the incident energy. Thus the received signal pulses from the test section were reduced in level by twice this amount or about -40 db relative to P_0. While this power loss tends to place a lower limit on the power of the signal source, a level in the 1 to 5 milliwatt range has been found to be adequate.

The shuttle-pulse measuring technique with an iris has several attractive features. It separates the input waveguide circuits which have large losses from the low loss waveguide being measured. With a line whose one-trip loss is a fraction of a decibel, the shuttle-pulse method permits the loss to accumulate for a number of trips, thus permitting an improved measurement accuracy. The results presented herein were based on measurements of 10 to 30 round-trips.

The 33 to 38 kmc measurements were made with a two-klystron set-up. The signal pulse was obtained from one of the klystrons by introducing a short pulse in the repeller circuit so that oscillations occurred only during the pulse interval. The other tube provided the continuous-wave beating oscillator signal.

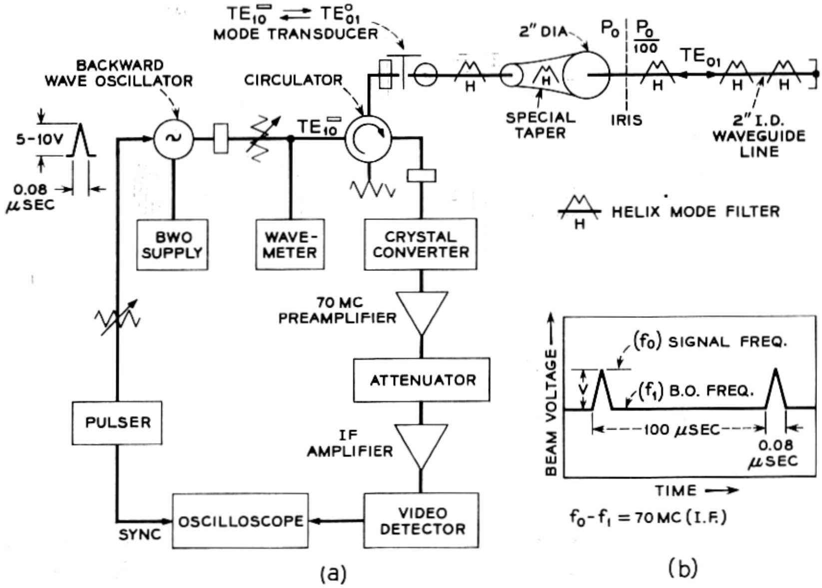

Fig. 2 — (a) Measuring circuit and (b) modulation scheme for shuttle-pulse method of measuring TE_{01} losses.

For the 41 to 90 kmc band backward-wave oscillators were used. A single oscillator tube was employed in a special measuring circuit [Fig. 2(a)] proposed by Ring[8] to provide both the transmitted signal pulse and the receiving beating oscillator power. The modulation scheme required to do this is shown graphically in Fig. 2(b). Here the modulating pulse amplitude of a few volts is adjusted to a voltage v such that at the top part of the pulse the oscillator frequency is shifted to frequency f_0. The steady-state unmodulated frequency of the oscillator is f_1. The intermediate frequency is $f_0 - f_1 = 70$ mc. Thus, after the pulse, the beam voltage is restored to the steady-state condition and supplies continuous beating oscillator signal between signal pulses. The 0.08-microsecond pulse width is dictated by the bandwidth of the receiving circuitry; the 100-microsecond repetition rate permits the energy at the signal frequency f_0 to decay before a new pulse is generated. The beating oscillator power impressed upon the converter is the reflection of the forward power from the front face of the iris; it is higher than the pulses from the section of line under test by a factor of twice the iris coupling, which is about 40 db. This condition ensures a good signal linearity.

Ring's circuit is an important advance in measurement techniques.

The advantages are that the frequency of a backward-wave oscillator can be closely set and the single-tube pulse method provides more convenient and faster measurements.

The waveguide components mounted between the signal source, the crystal converter, and the TE_{01} wave transducer were in rectangular waveguide and were of more or less conventional form. The wave transducer has been described elsewhere.[9] A helix waveguide mode filter was connected at the TE_{01} output of the transducer to minimize spurious mode impurities and a special taper[10] matched the transducer to the two-inch waveguide line. The taper section was designed to minimize conversion to higher-order TE_{0n} modes, especially the TE_{02} mode. The iris, which has already been described, was placed at the input of the section of line to be measured.

Three helix waveguide sections 10 to 15 feet long, which served as spurious-mode filters, were employed in the solid-copper test line. Two of these mode filters, one at each end of the line, were necessary in order to eliminate accumulative mode conversion-reconversion effects with successive trips and to ensure that each trip had the same TE_{01} transmission characteristic and loss. The third mode filter was placed approximately in the middle of the line. Its purpose was to reduce the continuous length of solid-copper waveguide to half the length, from 400 to 200 feet for the line described. The presence of this additional mode filter had a negligible effect upon the average TE_{01} loss, but the shorter run of solid-copper waveguide reduced the length over which continuous mode interaction could occur and resulted in smaller variations in TE_{01} loss with frequency.

IV. EXPERIMENTAL RESULTS

The observed data were plotted in terms of the one-way transmission loss as a function of frequency. The measurements were made on a round-trip basis and have been corrected for end losses. These include both the end loss and coupling loss at the iris and the loss due to the short at the end of the line.

The measured data for an all-helix line, a solid-wall-copper waveguide line, and the theoretical loss for solid-wall copper are plotted in Fig. 3 in db per mile as a function of frequency.

The smooth dashed line curve in Fig. 3 represents the loss which is based on the measurements of helix lines varying in length from 415 feet to over 1500 feet. These measured data have been extrapolated so that the ordinate values express the loss in db per mile. The theoretical loss curve is also in db per mile. At the lowest frequency, 33 kmc, the meas-

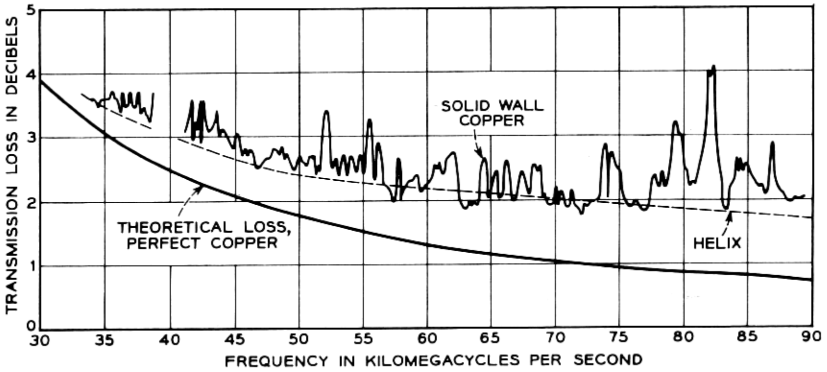

Fig. 3 — TE_{01} loss versus frequency.

ured loss is 3.7 db per mile; at 60 kmc, the loss is 2.2 db per mile; and at 90 kmc, the highest frequency measured, the loss is 1.7 db per mile. At 55 kmc, the helix loss is in good agreement with values determined on individual sections with a Q-measuring set.[11] The ratios of the measured to the theoretical attenuation at these frequencies are 1.11, 1.67, and 2.3 respectively. Thus, while the measured loss of this line relative to the theoretical value increased with frequency, the actual loss was still decreasing at the highest frequency measured. It is, therefore, presumed that the transmission loss of the helix line will be less than 1.7 db at frequencies above 90 kmc. The smoothness of this transmission loss curve is the result of the continuous mode-filtering action of helix waveguide.

The measured data obtained with a solid-wall-copper waveguide 443 feet long are shown by the upper solid line curve of Fig. 3. The loss is plotted on a relative basis for reasons which are mentioned below. The fluctuations in the TE_{01} loss which occurred in this line are due to mode conversion-reconversion effects that resulted from imperfect waveguide geometry. These variations in loss were relatively small at the lower frequencies, but in the vicinity of 80 kmc and above there were undesirably high loss peaks.

For similar lines with the same mode filter spacing the average loss increases linearly with length. The results for the 443-foot line may also be extended by using the analysis of random imperfections[3] to give the statistical properties of a much longer line. Thus, for a longer line with the same mode-filter spacing, the rms fluctuations in TE_{01} loss will increase by the factor $\sqrt{n}$, where n represents the number of 443-foot sections which are required for the longer line. Both the average loss

TABLE I

	Frequency					
	33–38 kmc	41–50 kmc	50–60 kmc	60–70 kmc	70–80 kmc	80–90 kmc
Helix line average loss, db per mile	3.38	2.75	2.29	2.11	1.92	1.79
Solid-wall copper average loss, db per mile	3.53	2.90	2.49	2.25	2.21	2.42
Solid-wall copper rms variation in db for line 1 mile long	0.050	0.043	0.078	0.074	0.118	0.141

and the rms fluctuations of the solid wall are computed from the measured data of Fig. 3 for a line one mile long in Table I. The average loss of the helix line is included. These data are for 10 kmc frequency bands above 50 kmc, and for the 33 to 38 and the 41 to 50 kmc bands below 50 kmc. The data of Table I were prepared by C. W. Curry.

V. CONCLUSIONS

The observed TE_{01} transmission losses over a frequency band of nearly 3-to-1 (33 to 90 kmc) show low transmission losses. At the lower frequencies both lines show an increasing attenuation with decreasing frequency which approaches the theoretical value at 33 kmc. The helix line shows a decreasing loss as the frequency increases, and is still decreasing at 90 kmc, the highest frequency of measurement. Above 70 kmc the solid-wall-copper line exhibits increasing loss with frequency. This is due to mode conversion-reconversion effects. Of the two lines, the helix waveguide has a lower attenuation and a smoother transmission characteristic.

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