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Measurement of Surface Resistance in Oversized Circular Waveguide at Millimeter Wavelengths

SATOMI HATANO AND FUMIHIRO NIHEI

***Abstract*—The increase of the surface resistance of oversized circular waveguides has been accurately evaluated at millimeter wavelengths by measuring attenuations of TE_{0n} modes. The ratios of the effective resistances to the ideal resistances of the wall were found to be 1.27, 1.42, and 1.54 at 40, 60, and 80 GHz, respectively.**

I. Introduction

There have been few reports or measurement values about surface resistances of oversized circular waveguides at millimeter wavelengths, since it has been very difficult to measure them directly. The difficulty of the measurement is attributed to the mode conversion from the signal mode to spurious modes. Then, in the calculation of attenuation in the circular waveguide, the surface resistance at the waveguide wall has been estimated by $R = \sqrt{\pi f \mu / \sigma}$ with conductivity of copper $\sigma = 5.8 \times 10^7$ ℧/m. Measured losses, however, are usually greater than those theoretically determined by the formula. The discrepancies between them have been regarded as mode conversion losses caused by waveguide imperfections.

Such consideration is reasonable only when the waveguide wall has ideal conductivity and has a relatively smooth surface compared with skin depth. The surface of the practical waveguide wall is generally rough, and the conductivity of the wall, which is electroplated with copper, is not always equal to the ideal one in the region of millimeter wavelengths. Therefore, it is assumed that the surface resistance increases on account of the inferiority of the waveguide wall caused mainly by roughness.

Even though the effect of surface roughness has been investigated and a number of results are reported, some are concerned with single-mode rectangular waveguide [1]–[3] and others with small samples of the metal plates [4], [5]. This short paper describes the surface resistance of oversized circular waveguides used as long-distance transmission lines at frequency regions from 40 to 90 GHz. The surface roughness of the waveguide wall is also discussed briefly.

II. Evaluation of Surface Resistance

A. Principles

Nomenclature

α_D	total attenuation in dielectric lined waveguides under ideal conditions;
α_M	measured attenuation in actual waveguides;
α_H, α_H'	heat loss due to surface resistance in ideal and actual waveguides, respectively;
$\Delta\alpha_1$	perturbation of attenuation due to dielectric losses;
$\Delta\alpha_2, \Delta\alpha_2'$	perturbation of attenuation due to additional eddy current caused by the dielectric in ideal and actual waveguides, respectively;
$\delta\alpha$	additional attenuation due to mode conversion;
R, R'	ideal and effective surface resistances, respectively.

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The authors are with the Ibaraki Electrical Communication Laboratories, Nippon Telegraph and Telephone Public Corporation, Tokai, Ibaraki, Japan.

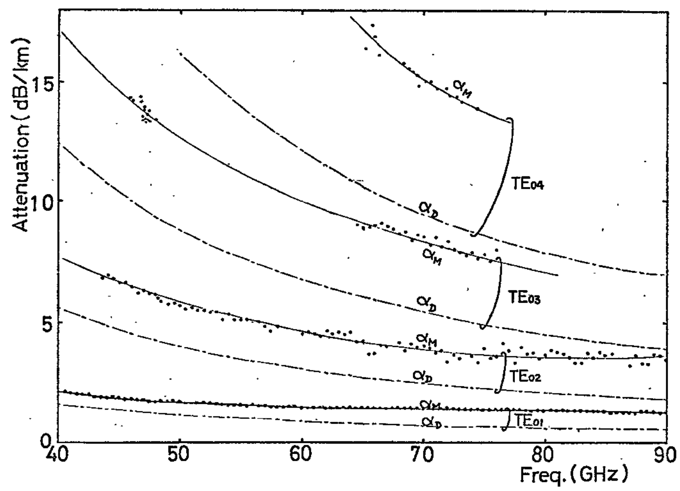

Fig. 1. Measured and calculated attenuation characteristics for TE_{0n} modes. α_M: measured characteristic for experimental guides. α_D: calculated characteristic for ideal guides.

Let us consider the TE_{0n} mode loss in perfectly straight and circular lined waveguides. The loss is given by the following equation [6]:

$$\alpha_D = \alpha_H + \Delta\alpha_1 + \Delta\alpha_2. \tag{1}$$

On the other hand, measured loss α_M in actual waveguides, which is expected to be larger than α_D because of various imperfections including surface roughness, is expressed as follows:

$$\alpha_M = \alpha_H' + \Delta\alpha_1 + \Delta\alpha_2' + \delta\alpha. \tag{2}$$

Here α_H' and $\Delta\alpha_2'$ mean the actual values of α_H and $\Delta\alpha_2$, respectively, and can be written as follows in terms of effective surface resistance R':

$$\alpha_H' = \alpha_H \frac{R'}{R}$$

$$\Delta\alpha_2' = \Delta\alpha_2 \frac{R'}{R}. \tag{3}$$

$\delta\alpha$ accounts for mode conversion loss due to mechanical imperfections in waveguides and joints. Being independent from surface resistance $\Delta\alpha_1$ in actual waveguides is regarded as the same value as in ideal waveguides.

The ratio of effective surface resistance R' to ideal surface resistance R can be carried out by (1)–(3) and then becomes

$$\frac{R'}{R} = \frac{\alpha_M - \Delta\alpha_1 - \delta\alpha}{\alpha_D - \Delta\alpha_1}. \tag{4}$$

B. Measurement of TE_{0n} *Mode Attenuation*

The attenuation characteristics of the 180-m-long experimental waveguide line by the pulse single-reflection method [7] have been measured, which makes it possible to measure low losses with high accuracy. The waveguide line under measurement,

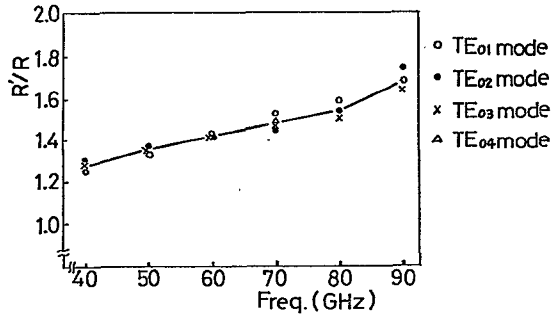

Fig. 2. R'/R characteristics derived from TE_{0n} mode attenuations.

TABLE I
CALCULATED VALUES OF $\Delta\alpha_1$ AND $\delta\alpha$

Term	Mode \ Freq.(GHz)	40	50	60	70	80	90
$\Delta\alpha_1$ (dB/km)	TE_{01}	0.02	0.02	0.03	0.03	0.04	0.04
	TE_{02}	0.06	0.07	0.09	0.10	0.12	0.13
	TE_{03}	0.14	0.16	0.19	0.22	0.25	0.28
	TE_{04}	0.26	0.30	0.34	0.39	0.44	0.48
$\delta\alpha$ (dB/km)	TE_{01}	0.14	0.18	0.25	0.34	0.44	0.54
	TE_{02}	0.29	0.28	0.30	0.36	0.44	0.52
	TE_{03}	0.90	0.69	0.60	0.59	0.61	0.67
	TE_{04}	2.70	1.75	1.35	1.14	1.05	1.00

whose mechanical imperfections are suppressed as much as possible in order to reduce the mode conversion losses, consists of 30 lined-waveguide sections with 200-μm polyethylene lining and 51 mm ID, and 6 helix-waveguides sections which work as mode filters for all but TE_{0n} modes. The length of each section is 5 m. The measurements were carried out for four modes, TE_{01}, TE_{02}, TE_{03}, and TE_{04} modes, at the frequencies between 40 and 90 GHz. The measured results are illustrated in Fig. 1 as α_M. The loss characteristics calculated for an ideal lined-waveguide line with smooth surface are also shown in the same figure as α_D. It can be mentioned that there exist rather large discrepancies between measured values and calculated values for each mode. These discrepancies should be attributed to waveguide and joint imperfections, surface roughness, etc.

C. Evaluation of R'/R

In order to evaluate the ratios R'/R in terms of (4), the three terms of α_D, $\Delta\alpha_1$, and $\delta\alpha$ also need to be calculated besides α_M. The former two terms can be easily calculated according to Unger's equations [6]. The third term $\delta\alpha$, however, depends on the conditions of the waveguide. Then measurements of imperfections, such as straightness deviation, ellipticity, tilt, offset, etc., have been carried out with regard to the experimental waveguide. Consequently, the additional loss $\delta\alpha$ due to line imperfections can be calculated for each TE_{0n} ($n = 1, 2, 3,$ and 4) mode. In the calculation of $\delta\alpha$, any spurious modes which couple to the signal mode are taken into account. The calculated values of $\Delta\alpha_1$ and $\delta\alpha$ for the four modes are shown in Table I.

TABLE II
AVERAGED RATIOS OF R'/R

Freq.(GHz)	40	50	60	70	80	90
R'/R	1.27	1.36	1.42	1.48	1.54	1.69

Since the measured values of TE_{0n} mode attenuation and the calculated values are obtained for the waveguide as α_M, α_D, $\Delta\alpha_1$, and $\delta\alpha$, the ratios of the effective resistance R' to the ideal resistance R can be calculated by (4). Fig. 2 shows the characteristics of R'/R for TE_{0n} modes at several frequencies. Even though there may exist errors of R'/R because of measurement errors of TE_{0n} attenuations and mechanical imperfections, after evaluation of R'/R for several modes the accuracy can be explained by a comparison between them. If the errors are not small or the equations not valid, values of R'/R will scatter for each mode. According to Fig. 2, it becomes clear that the values of R'/R, derived independently for the TE_{0n} modes, are in excellent agreement with one another. This proves that the procedures which are used to gain R'/R are valid and measurement values have small errors. Furthermore, the total variation in R'/R for the four modes, carried out from Fig. 2, is under 6 percent for all frequencies.

III. DISCUSSION

The R'/R values have been obtained from the attenuation of TE_{0n} modes and are found to be in good agreement with one another. After calculation of the average of the ratios of R'/R, the final ratios are determined, which are shown in Table II. As a result, the average ratios of the effective resistance to the ideal resistance of the waveguide wall are found to be 1.27, 1.42, and 1.54 at 40, to 60, and 80 GHz, respectively. Such increases of the surface resistance are unexpectedly large. It seems that the increases are caused mainly by surface roughness. It is observed that the surface of the waveguide wall has such considerable roughness as 1 μm_{p-p} by surface roughness measurement. Theoretical studies on correlations between the increase of resistance and the surface roughness, however, need to be done after more accurate observations of surface conditions.

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