Measurements on Dielectric and Radiation Loss of Flexible Circular Dielectric Waveguides in Q-Band

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Abstract — **In Q-band, dielectric losses and radiation losses of flexible circular PTFE waveguides are measured with parameters such as operating frequency, areas of the dielectric region in guiding cross sections, and radii of curvature. The dielectric losses of the rod and tube waveguides show relatively good agreement with theoretical results. The radiation losses of the guides, which current theory cannot predict in the regime of small radius of curvature, are measured from differences between insertion losses and the dielectric losses. The validity of our results can be explained by the fractional power flow ratios in each region of the waveguides.**

I. Introduction

In millimeter wave frequencies, propagation losses of dielectric waveguides are known to be much smaller than those of their metal counterparts. Elsasser [1] and Kharadly *et al.* [2] calculated attenuations of a dielectric rod and a hollow tube waveguide, respectively. Chandler [3] investigated the possibility of a dielectric rod as a low loss wave guiding structure, experimentally. Jablonski [4] measured the attenuation characteristics of the circular dielectric waveguides at 72.70GHz. Owing to their low loss characteristics and a mechanical flexibility of some commercial polymer dielectrics such as a polystyrene, a polyethylene, a polypropylene, and a PTFE [5], dielectric waveguides can be considered as low cost flexible waveguides [6]-[7] comparable to commercial flexible waveguides, which consist of metal corrugations [8]. When using the dielectric guide as a flexible waveguide, however, an additional radiation is generated at bending. This is because the phase velocity of the open waveguide exceeds the velocity of a plane wave in the surrounding medium and a radiation begins to take place at some radius of curvature [9]. Theoretical radiation loss as a function of the operating frequency, the radius of curvature, and the guiding medium is, as we know of, not established rigorously yet. Only the case that the radius of curvature is much larger than the diameter of the guide is described approximately [10]. Previous results of various flexible waveguides in millimeter wave frequencies focused on determining both total attenuations and lower limits of the curvature radii or upper limits of the bent angle that are negligible to the total attenuations [6]-[7], [11]-[13]. In order to determine the radiation loss of the flexible dielectric waveguides, redistributed electro-magnetic fields at curved section of the guides relative to the reference straight guide should be known, in advance. The redistributed fields caused by the bend, however, are difficult to describe and analyze [14]. Furthermore, there has not been concrete formula to describe the radiation loss, precisely, for both the rods and the tubes, in millimeter wave band. If one interests the flexible dielectric waveguides as a practical use, the amount of the radiated power at bend needs to be investigated. Since the radiation loss is strongly dependent upon the design parameters, the effects of the design parameters on the radiation loss need to be studied.

In this paper, we measured the dielectric loss and the radiation loss of the circular PTFE waveguides in Q-band (33GHz to 50GHz) with variations of parameters such as frequency, guiding cross sections, and radii of curvature. The measured dielectric loss shows relatively good agreement with theoretical results. From differences between the measured dielectric loss and the insertion losses of the bent waveguide, we determined the radiation loss with the parameters such as operating frequencies, guiding cross sections, and the radii of the curvatures. The dielectric and radiation losses were explained by the fractional power flows in each region of the guides, qualitatively.

II. Design of the Dielectric Waveguides

For practical use as a flexible waveguide, the dielectric materials must possess a mechanical flexibility. Generally, dielectrics tend to be hard and rigid as they have higher dielectric constant. Thus we choose PTFE as a guiding medium, whose dielectric constant in Q-band are assumed to be 2.08 [4]-[5]. The loss tangent of PTFE is obscure in Q-band [4]-[5].

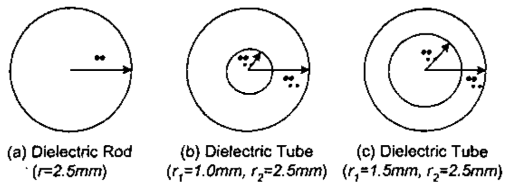


Fig. 1. Structure of various dielectric waveguides

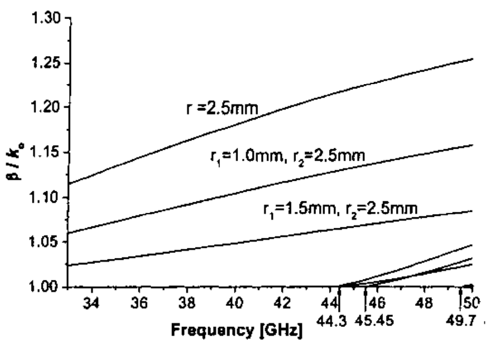


Fig. 2. Dispersion curve of various dielectric waveguides

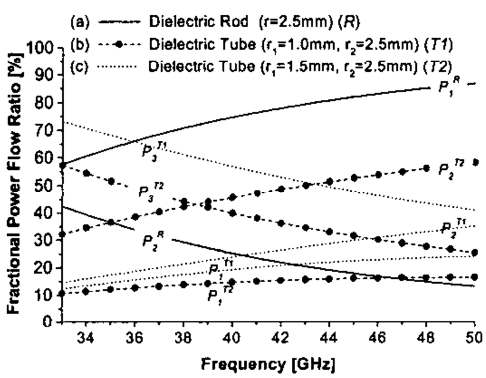


Fig. 3. Fractional power flow ratios of varius dielectric waveguides

We assumed the loss tangent of PTFE to be 0.0001 for this research. Fig. 1 shows cross sections of the dielectric circular waveguides employed in this work. The environmental surroundings and hollow region (origin to r_1) of the tubes are the free spaces. In order to calculate the dielectric loss of the circular dielectric waveguides operated by the fundamental HE_{11} mode, we determined the outer radii of the guides as 2.5mm (r for the rod and r_2 for the tubes) from the dispersion relation [15]. Fig. 2 is a dispersion curve for the waveguides employed in this work. The vertical axis represents normalized propagation constants, that is, propagation constants normalized with the free space wave number, k_0. As shown in Fig. 2, the second mode cutoff frequency for the rod waveguide with a radius of 2.5mm was 44.3GHz. We set the outer radii of the tubes as same as the rod one, and chose the inner radii as a 1.0mm and a 1.5mm. The cutoff frequencies of the tubes, whose inner radii are 1.0mm and 1.5mm, are 45.45 GHz and 49.7GHz, respectively. The cutoff frequencies of the second mode shifted toward the higher frequency regime, with a decrease in the thickness (r_2-r_1) of the tubes. The thickness of the tube whose inner radius is 1.5mm (Fig. 1(c)) is 1.0mm, which do not affect to a deformation of the tube when the tube is bent or is suffered to an external force.

The dielectric losses of the waveguides are determined by the perturbation method [16] as in (1).

$$\alpha_d = \frac{8.686}{100} \times \frac{P_L}{2P_T} [dB/cm] \quad (1)$$

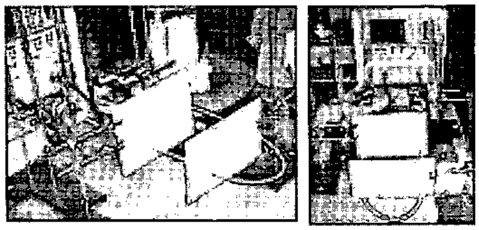
where P_T and P_L are the power propagated and the power lost per unit length, respectively, and 8.686 is a factor from neper to dB scale.

$$P_T = \frac{1}{2}\int_0^{\infty} \left(E_r H_\theta^* - E_\theta H_r^* \right) rdr \quad (2)$$

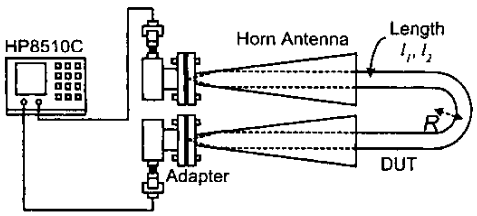
$$P_L = \frac{\omega \varepsilon_0 \varepsilon_r \tan\delta}{2} \int_{\substack{Dielectric \\ Region}} \left(|E_r|^2 + |E_\theta|^2 + |E_z|^2 \right) rdr \quad (3)$$

In (2) and (3), field components in the dielectric region and the free space region are governed by the Bessel functions and modified Bessel functions, respectively [15]. Using (2), we calculated the fractional power flow ratios. Fig. 3 shows the fractional power flow ratios with the operating frequency. The propagating power P_T is a sum of the propagating power in each region, e.g., P_1^R and P_2^R for the power propagated in the dielectric region and in the free space region of the rods, respectively; $P_1^{T1,2}$, $P_2^{T1,2}$, and $P_3^{T1,2}$ for the power propagated in a air core region, in the dielectric region, and outside free space region of the tubes, respectively. The superscripts R, $T1$, and $T2$ represents for the waveguides in Fig. 1(a), (b), and (c), respectively. The propagating powers in the dielectric region (P_1^R of Fig. 3(a), P_2^{T1} of Fig. 3(b), and P_2^{T2} of Fig. 3 (c)) and in the free space region inside the tube (P_1^{T1} of Fig. 3(b) and P_2^{T1} of Fig. 3(c)) are confined with an increase in the frequency and the areas of the dielectrics in the cross sections.

The calculated value of the attenuation per unit length will be shown and compared with the measured results in section IV.



(a) Photographs



(b) Schematic diagram. (R : Radius of curvature)

Fig. 4. Experimental setup.

TABLE I

TOTAL LENGTHS AND RADII OF CURVATURE OF THE SAMPLES EMPLOYED IN THIS WORK

Types	Length, l_1 [cm]	Length, l_2 [cm]	Curvature Radius, R [cm]
Rod (*r*=2.5*mm*)	101	72	3, 5
Tube (*r*₁=1.0*mm*, *r*₂=2.5*mm*)	201	90	3, 5, 7
Tube (*r*₁=1.5*mm*, *r*₂=2.5*mm*)	200	90	3, 5, 7, 9

III. MEASUREMENTS

Fig. 4 shows photographs and a schematic diagram of the experimental setup. Experiments were performed with HP8510C vector network analyzer to get scattering parameters. The 25dB standard gain horn antennas were used for efficient launching and receiving signals of the vector network analyzer. The guides were inserted into the horn to the end. The central position in the horn and the semicircle shape of the bending section of the guide are fixed with the foam, whose dielectric constant and loss tangent can be considered as same as the free space [5], so that the perturbation by the foam is so small enough to be negligible. Both tips of the rod were tapered in order to reduce the return loss achieving approximately below -20dB. The return losses of the tubes were also below -20dB without any tapering. It means that reflected powers are much small enough to be negligible. In order to determine the attenuations per unit length of the straight guide, we measured the insertion losses of some samples with different lengths including the bending section. Table I is a list of samples used in this measurement. Since the radiations at bend with the same curvature radius would be same for two different length samples, we can calculate the attenuations per unit length of each waveguide at straight using (4).

$$\alpha_d = -\frac{10Log_{10}\left[1-\left(10^{S_{21,l_2}/10}-10^{S_{21,l_1}/10}\right)\right]}{l_1-l_2} \; [dB/cm] \quad (4)$$

where S_{21,l_1} and S_{21,l_2} are the measured insertion losses of the different samples at the same specific radius of curvature. We assumed that the dielectric losses along the straight guide and along the curved guide are not so different compared with the radiation loss. Accordingly, we can separate the dielectric loss and the radiation loss from the measured insertion losses. The radiation per unit angle can be obtained from the difference between the dielectric loss and the measured insertion loss as in (5).

$$\alpha_r = -\frac{10Log_{10}\left[1-\left(10^{-\frac{\alpha_d}{10}\times l_1}-10^{S_{21,l_1}/10}\right)\right]}{180} \; [dB/Deg.] \quad (5)$$

In the experimental setup of Fig. 4, the bent angle is 180°, so the difference between the dielectric loss and the insertion loss, *i.e.*, the radiation loss, must be divided by the bent angle in order to represent the radiation per unit angle.

IV. RESULTS AND DISCUSSIONS

From the measured insertion loss, we determined the attenuations per unit length of the flexible dielectric waveguides using (4). Fig. 5 shows the attenuation per unit length. The dielectric losses of each guide were below 0.01dB/cm for all frequency band, and show relatively good agreement with the theoretical value. The dielectric losses increase with the frequency. The dielectric loss of the rod waveguide is higher than that of the tube waveguides. This result can be explained by more propagating power confinement in the dielectric region with an increase in the frequency and the dielectric area of the guiding cross section, which is shown in Fig. 3.

The radiation loss can be calculated from the difference between the measured insertion loss and the dielectric loss as in (5). Fig. 6 shows the radiation per unit angle. The radiation loss of the rod waveguide is lower than that of the tube waveguides. The radiation decreases with an increase in the operating frequency.

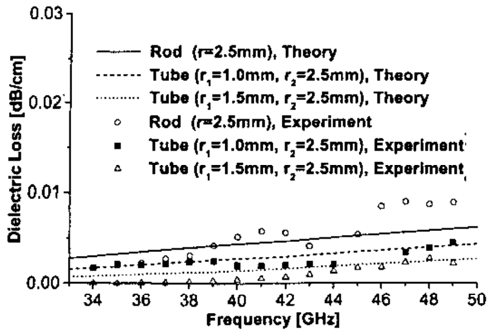


Fig. 5. Dielectric loss of various flexible waveguides

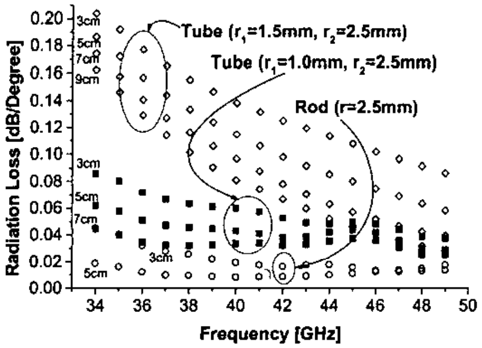


Fig. 6. Radiation loss of various flexible waveguides

As the radius of curvature decreases, the guided power is reduced, indicating that the power radiated to the free space increases. The radiation per unit angle decreases rapidly, as the dielectric area in the guiding cross section increase. The radiation loss has an opposite tendency with the dielectric loss because the radiated power is inversely proportional to the power confined in the dielectric region as shown in Fig. 3.

V. CONCLUSION

We measured the dielectric and radiation loss of the circular flexible PTFE rod and tube waveguides in Q-band. The dielectric losses were obtained below 0.01dB/cm from the difference of the insertion loss measured between waveguide samples with different lengths. The dielectric loss increases as the frequency and the dielectric region in the guiding cross section increase. The radiation loss, which current theory cannot predict in the regime of small radius of curvature, was measured from difference between the dielectric loss and the measured insertion loss. The radiation loss decrease as the frequency, the dielectric region in the guiding cross section, and the curvature radii increase.

ACKNOWLEDGEMENT

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