Loss Characteristics of Flexible Dielectric Tube Waveguides using Commercial Polymer Substances in Millimeter Wave Band

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ABSTRACT

Propagation losses including both transmission losses and bending losses of the flexible dielectric tube waveguide using commercial polymer substances for a short distance millimeter wave transmission are analytically predicted. The transmission loss and the bending loss are strongly dependent on the power flow distributions in each region. The obtained propagation losses are compared with those of the commercial metal rigid and flexible waveguides.

I. Introduction

Lack of frequencies in the microwave bands commonly used is the important reason today to move into the millimeter wave frequency regime. Millimeter wave systems are small in size and light weight, compared with their microwave counterparts. Waveguides are core components in the microwave and the millimeter wave systems. The development of the proper waveguiding structures in millimeter wave frequencies has been receiving lots of attentions for quite recent years. Conventional metal waveguide used at millimeter wave frequencies is rigid, expensive and its attenuation is sufficiently high. The principle source of the attenuation is the ohmic loss of the induced surface currents in the wall of the guide. If there are no conducting surfaces, the ohmic loss is not a concern. In this sense, dielectric waveguide is suitable for the transmission of the millimeter wave frequencies because it has relatively low loss characteristic and dimensions are of an order that can be easily fabricated and handled. Furthermore, if it can be bent freely, the application areas will be enlarged and expected to be used widely. For developing flexible dielectric waveguides, the wave guiding mediums must have properties such as low loss characteristic, flexibility, mechanical stability or strength. Commercial polymer dielectric materials such as polytetrafluorethylene(PTFE, Teflon[R]), polypropylene, polyethylene, polystyrene, etc, are promising candidates for this flexible waveguide application, because they have low attenuation characteristics($\tan\delta \sim 10^{-4}$), fair flexibilities and low costs. Referring to reference[1], we can assume that relative dielectric constants and loss tangents of some common commercial polymer dielectrics have the following values as seen in Table. 1. From the standpoint of the geometry, the waveguides with cylindrical geometry can be most easily considered for the flexible waveguide application.

Substances	ε_r	$\tan\delta$
PTFE	*2.08*	*0.0005*
Polypropylene	*2.20*	*0.0005*
Polyethylene	*2.05*	*0.0005*
Polystyrene	*2.54*	*0.0005*

Table 1. Relative Dielectric Constants and Loss Tangent of some Commercial Polymer Dielectrics at 38 GHz.

They are various cylindrical waveguides such as dielectric rod waveguides(two region dielectric waveguide), three region dielectric waveguides, and multiple layered dielectric waveguides. Sugi *et al.*[2] proposed the dielectric tube waveguide(*O*-guide), and Kharadly *et al.* [3] studied the mode designation and the propagation char-acteristics for all modes of the dielectric tube waveguide. The dielectric tube waveguide often has lower attenuation characteristics than the dielectric rod waveguide and a simpler structure to manufacture. Previously, we have studied on the dielectric tube waveguide for the cases of some ideal dielectric constants (2, 3, 4) [4]

In this paper, the propagation characteristics of the cylindrical dielectric tube waveguide using some commercial polymer dielectrics are investigated 38GHz. Mode characteristics and single mode operation conditions from the characteristic equations are analyzed.

The correlations between loss characteristics such as transmission losses and bending losses and propagating power distributions in each region are examined. Total propagation losses including both the transmission losses and the bending losses are compared with those of the commercial metal rigid waveguides and flexible waveguides. Note that the scattering losses from the dielectric surface roughness or imperfection are not considered in this work.

II. Characteristics of Dielectric Tube Waveguides

A. Guided Mode Formulation

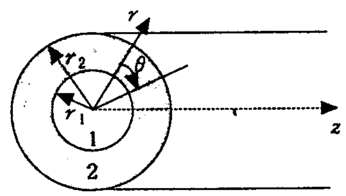


Fig. 1. Dielectric Tube Waveguide

Fig. 1. is the geometry of a cylindrical dielectric tube waveguide. Regions 1, 2, and 3 are the air core region ($\varepsilon_{r1}=1$), dielectric tube region ($\varepsilon_{r2}>1$) and the outer air region ($\varepsilon_{r3}=1$), respectively. Choosing the cylindrical coordinate system and the Bessel functions with the proper behavior at the origin and infinity, the axial field components of each region can be expressed as the followings.

$$E_{z1}=A\,I_m(k_1 r)\cos m\theta\, e^{j(\omega t-\beta z)} \quad (1)$$

$$H_{z1}=B\,I_m(k_1 r)\sin m\theta\, e^{j(\omega t-\beta z)} \quad (2)$$

$$E_{z2}=[C\,J_m(k_2 r)+D\,Y_m(k_2 r)]\cos m\theta\, e^{j(\omega t-\beta z)} \quad (3)$$

$$H_{z2}=[E\,J_m(k_2 r)+F\,Y_m(k_2 r)]\sin m\theta\, e^{j(\omega t-\beta z)} \quad (4)$$

$$E_{z3}=G\,K_m(k_3 r)\cos m\theta\, e^{j(\omega t-\beta z)} \quad (5)$$

$$H_{z3}=H\,K_m(k_3 r)\sin m\theta\, e^{j(\omega t-\beta z)} \quad (6)$$

J_m and Y_m are the Bessel functions of the first and second kind; and I_m and K_m are the modified Bessel functions of the first and second kind. Here m is the azimuthal eigenvalue; A, B, C, D, E, F, G and H are constants to be determined; and the real constants, k_1, k_2, and k_3 are defined by

$$k_1^2=k_o^2(\overline{\beta}^2-\mu_{r1}\varepsilon_{r1}) \quad (7)$$

$$k_2^2=k_o^2(\mu_{r2}\varepsilon_{r2}-\overline{\beta}^2) \quad (8)$$

$$k_3^2=k_o^2(\overline{\beta}^2-\mu_{r3}\varepsilon_{r3})=k_1^2 \quad (9)$$

Here the region of $\mu_{r2}\varepsilon_{r2}\geq\overline{\beta}\geq\mu_{r1}\varepsilon_{r1}$ $(=\mu_{r3}\varepsilon_{r3})$ is considered, where $\overline{\beta}=\beta/k_o$ is normalized propagation constant and k_o is free space wave number.

B. Propagation constants

From the axial component of the field, we can readily obtain the transverse components of the field in each region from the Maxwell's curl equations. At the boundaries $r=r_1$ and $r=r_2$, the tangential components of the fields must be continuous, resulting in a set of eight equations with eight unknowns. The characteristic equation is obtained by setting the determinants of the 8 ×8 coefficient matrix to zero. The existence of a nontrivial solution leads to an eigenvalue equation which determines the dispersion relation and field distribution of the guide. The mode with zero cutoff frequency has been traditionally referred to as the HE_{11} mode, which is a fundamental mode. We analyze the characteristics of the dielectric tube waveguides operated under this HE_{11} mode. The $k_o r_1$ cutoff values of TE_{01}, TM_{01} and EH_{11} modes are calculated with the various ratios of outer radius r_2 to inner radius (r_2/r_1) and relative dielectric constants. The TE_{01} mode has the lower values of cutoff for all the combinations. The HE_{11} mode exists below the cutoff of the TE_{01} mode. Table 1. shows $\overline{\beta}$ and $k_o r_1$ values of the HE_{11} mode for single mode operations.

r_2/r_1 \ ε_{r2}	2.08	2.20	2.25	2.54
1.1	1.01722 (4.25613)	1.01863 (4.03720)	1.01920 (3.95543)	1.02241 (3.56261)
1.2	1.03212 (2.97877)	1.03466 (2.82540)	1.03569 (2.76811)	1.04143 (2.49290)
1.3	1.04524 (2.40669)	1.04875 (2.28267)	1.05017 (2.23635)	1.05803 (2.01382)
1.4	1.05694 (2.06191)	1.06131 (1.95559)	1.06307 (1.91587)	1.07276 (1.72509)
1.5	1.06746 (1.82408)	1.07260 (1.72996)	1.07466 (1.69480)	1.08598 (1.52592)
1.6	1.07697 (1.64669)	1.08280 (1.56167)	1.08515 (1.52992)	1.09794 (1.37737)
1.7	1.08560 (1.50746)	1.09207 (1.42959)	1.09467 (1.40051)	1.10881 (1.26078)
1.8	1.09346 (1.39421)	1.10052 (1.32215)	1.10335 (1.29524)	1.11874 (1.16594)
1.9	1.10064 (1.29962)	1.10824 (1.23240)	1.11129 (1.20731)	1.12783 (1.08672)
2.0	1.10720 (1.21898)	1.11531 (1.15591)	1.11856 (1.13235)	1.13618 (1.01919)

Table 2. Normalized propagation constants (and their $k_o r_1$ values) of the HE_{11} mode

C. Power Flow Distribution

Power propagated along the guide in the axial direction, which is strongly dependent on the transmission loss and bending loss is considered. It is given by

$$P_T=\frac{1}{2}\int_0^{\infty}(E_r H_\theta^* - E_\theta H_r^*)\,r dr \quad (10)$$

and is related to

$$P_T=P_{T1}+P_{T2}+P_{T3} \quad (11)$$

where

$$P_{T1} = \frac{1}{2}\int_0^{r_1}(E_{r1} H^*_{\theta 1} - E_{\theta 1} H^*_{r1}) r dr \quad (12)$$

$$P_{T2} = \frac{1}{2}\int_{r_1}^{r_2}(E_{r2} H^*_{\theta 2} - E_{\theta 2} H^*_{r2}) r dr \quad (13)$$

$$P_{T3} = \frac{1}{2}\int_{r_2}^{\infty}(E_{r3} H^*_{\theta 3} - E_{\theta 3} H^*_{r3}) r dr \quad (14)$$

Using the normalized propagation constants in Table. 2 and equations from (10) to (14), we calculated the fractional power flow ratios in each region, as seen in the Fig. 2.

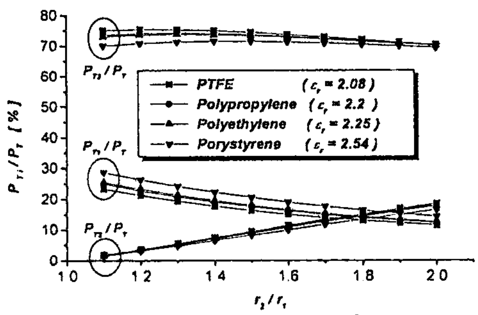


Fig. 2. Fractional Power Flow Distribution

From the analysis results of Fig. 2, we find out that the tubes with higher ratios of r_2 / r_1 (thicker tubes), and lower values of the relative dielectric constants have more tightly bound electromagnetic powers in the dielectric regions(Region 2). The fractional power flow ratios in region1(free space) decreases with the thickness of the tube, and also increases with relative dielectric constants of the tubes. In region 3(free space), the fractional power flow ratios do not change seriously with the thickness of the tubes. However, as the values of the relative dielectric constants become lower, the power propagating in the region 3 increases.

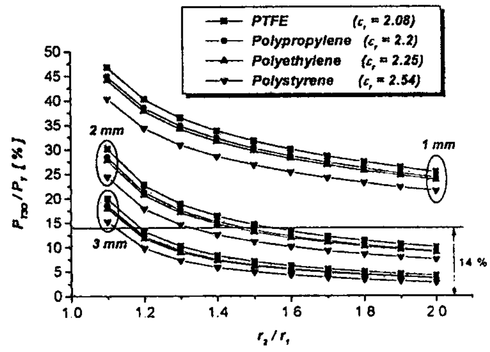
At this point, we can define another fractional power flow ratio, which describes the power containment from a certain distance ($r_2 + r_p$) to infinity per total propagating power as

$$P_{T3O}/ P_T \quad (15)$$

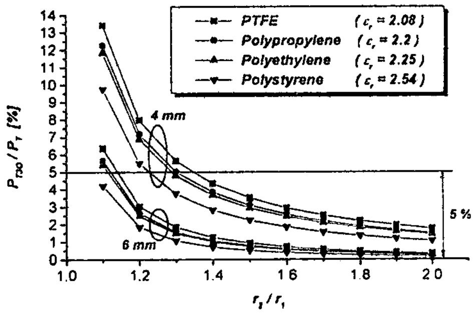
where

$$P_{T3O} = \frac{1}{2}\int_{r_2+r_p}^{\infty}(E_{r3} H^*_{\theta 3} - E_{\theta 3} H^*_{r3}) r dr \quad (16)$$

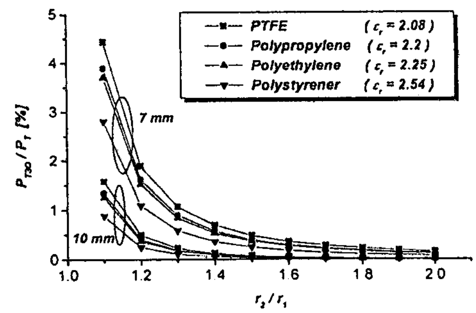
Fig. 3 shows the results of the fractional power flow ratios obtained from the equation(15). As shown in Fig.3, as the ratios of r_2/ r_1 in the tubes with higher relative dielectric constants increase, the P_{T3O}/ P_T [%] decreases, indicating that the high dielectric tubes with the higher ratios of r_2/ r_1 have an advantage over other tubes in concentrating more electromagnetic powers tightly near the outer surface of the tubes. Since the fields in the outer free space region are governed by the modified Bessel function of the second kind, i.e., $K(k_3 r)$, the magnitude of the fields decreases nearly exponentially, as r increases. This causes the rapid decrease of the electromagnetic power in the outer free space region.



(a) r_p = 1 mm, 2 mm, 3 mm



(b) r_p = 4 mm, 6 mm



(c) r_p = 7 mm, 10 mm

Fig. 3. Fractional Power flow Ratios in eq.(15)

D. Transmission Loss

Transmission loss from dielectric imperfection is given as follows:

$$\alpha_d = \frac{P_L}{2P_T} \quad (17)$$

where P_T is the power propagated along the guide at z given in (10), and P_L is the power lost per unit length at z, given by

$$P_L = \frac{\omega \varepsilon_0 \varepsilon_{r2} \tan\delta}{2} \int_{r_1}^{r_2} \left(|E_\theta|^2 + |E_r|^2 + |E_z|^2 \right) r dr \quad (18)$$

where $\tan\delta$ is the loss tangent of the dielectric tube. We assume that the power loss arises only from the dielectric tube. Figure 4 shows the transmission loss with the various ratios of r_2/r_1 and relative dielectric constants of the tube. As shown in Fig.4, the transmission losses range from 0.0005 to 0.0060 dB/cm.

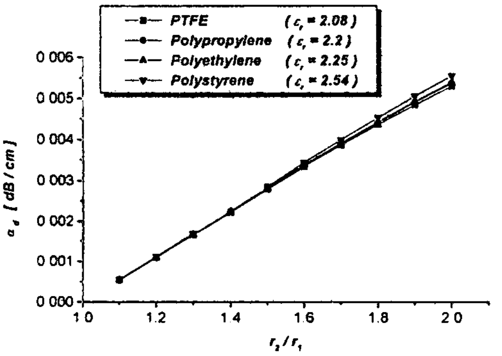


Fig. 4. Transmission Loss

The comparison of the fractional power flow ratio with the transmission loss, with the various ratios of r_2/r_1 and the relative dielectric constants of the tube shows that the structure with weakly confined power flow in the dielectric region has the lower transmission loss characteristic than that with strongly confined power flow. In addition, the tubes with the lower relative dielectric constants take advantage of the lower transmission loss characteristics.

E. Bending Loss

Bending loss arises from the radiation at bend. Referring to [5], we can use the following equation:

$$\alpha_r = \frac{1}{2}\sqrt{\frac{k_3}{R}} \exp\left[-\frac{2}{3} R k_0 \left(\bar{\beta}^2 - 1 \right)^{3/2} \right] \quad (19)$$

where R is the radius of curvature and k_3 is given in (9). Since the bending loss is mainly determined by the argument of the exponential function, we can expect that the larger normalized propagation constant gives the lower bending loss, if the radius of curvature is fixed. Therefore, it is important to take the point for the single mode operation on the dispersion curve of the HE_{11} mode just below the cutoff of the TE_{01} mode. Using the equation (19) and the normalized propagation constants in Table 2, we calculate the bending loss with the various dimensions and the various relative dielectric constants of the dielectric tube waveguides. We choose arbitrarily 5 cm and 10 cm as radii of curvature.

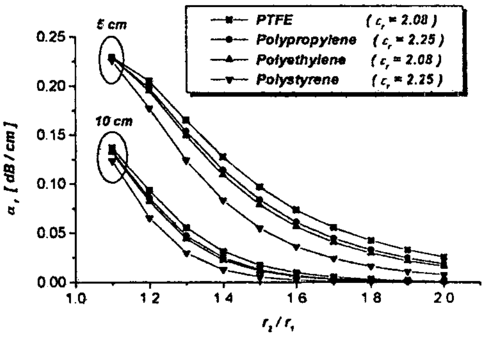


Fig. 5. Bending Loss
(R = 5 cm, 10 cm)

Fig. 5 shows the bending loss of the dielectric tube waveguides when the radii of curvature are 5 cm and 10 cm, respectively. As the ratios of r_2/r_1 and the relative dielectric constants increase, the bending losses decrease. This reduction is presumably due to the tight confinement of the electromagnetic power near the outer surface of the guide, as can be expected from the results of Fig. 3.

F. Total Loss and Benchmarks

Total propagation losses are considered as a summation of the transmission loss and the bending losses such as

$$\alpha = \alpha_d + \alpha_r \quad (20)$$

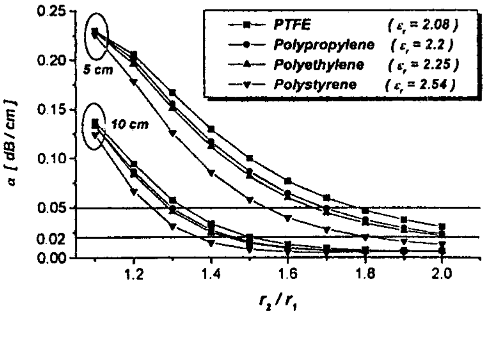


Fig. 6. Total Propagation Losses

Fig. 6 shows the total propagation losses obtained from the transmission losses and bending losses with the dimensions and the relative dielectric constants of the tubes. In the case of radii of curvature of 5 cm or 10 cm, the transmission losses are negligible compared with the bending losses. As seen in the Fig. 6, if we aim to design the flexible dielectric tube waveguide with total propagation loss of 0.05 dB/cm or 0.02 dB/cm, we can determine the ratio r_2 / r_1 or the corresponding materials that satisfies the design spec. Table 3. shows the losses of some commercial metal rigid and flexible waveguides. If we choose the optimal dimensions such as radius and thickness of the dielectric tube with the proper relative dielectric constants, we can obtain the low loss flexible dielectric tube, when compared with the some commercial metal rigid and flexible waveguides.

α_d (dB/cm)	α_r	Freq.(GHz)	Note	Ref.
0.008 -0.022		72.70	Teflon Rod	[6]
0.039 -0.125			Polystyrene	
0.004		80-200	Gas Confined Dielectric Tube	[7]
0.04		150	Polyethylene	[8]
0.019		33.0-50.0	Corrugated Metal	[9]
0.0052 -0.0076		26.5-40.0	Rect. W/G (Cu Alloy)	[10]
0.0077 -0.0113			Rect. W/G (Al Alloy)	
0.12 -0.26	4 cm *	94	Powder Core Dielectric	[11]
0.1	8 cm *	80-115	Metalized Teflon Tubing	[12]
0.0005 -0.006	0.0128 -0.2299# 0.0017 -0.1371##	38	Dielectric Tube Waveguide	This Work

* Radius of curvature that are negligible on the attenuation.
\# (##) Total propagation losses at 5cm(10cm) as a radius of curvature.

Table 3. Attenuations of Waveguides

III. Conclusions

Loss characteristics of the flexible dielectric tube waveguide using commercial polymer substances are analyzed at millimeter wave band. The attenuations at straight range from 0.0005 to 0.006 dB/cm. At the radii of curvature of 5 and 10cm, the total propagation losses including both the transmission losses and the bending losses range from 0.0128 to 0.2299 dB/cm and from 0.0017 to 0.1371 dB/cm, respectively.

Acknowledgement

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