FLEXIBLE MM-WAVE DIELECTRIC WAVEGUIDES

by
W.M. Bruno and W.B. Bridges
California Institute of Technology 128-95
Pasadena, California 91125

Flexible dielectric waveguides have been demonstrated at 10 GHz and 94 GHz by filling hollow, low-dielectric-constant polymer tubes with low-loss, high-dielectric-constant powders. Flexible guides with losses as low as 0.12 dB/cm were demonstrated at 94 GHz. These guides also exhibited negligible bending loss for radii of curvature greater than 4 cm.

1. 10 GHZ MODELING EXPERIMENTS

Initial efforts to make dielectric waveguides by filling flexible hollow tubes with dielectric powders were conducted at 10 GHz to avoid complications due to the small guide dimensions at 94 GHz. The powders used were Emerson and Cumming ECCO-FLO powder, Trans-Tech D-30 nickel-aluminum titanate, and Trans-Tech D-38 barium tetratitanate. The particles of the D-30 and D-38 powders ranged in size from 43 µm to 100 µm. Trans-Tech gives values of $\varepsilon' = 31$ and $\tan\delta < .0002$ for solid D-30 at 10 GHz, and $\varepsilon' = 37$ and $\tan\delta < .0005$ for solid D-38 at 6 GHz. ECCO-FLO powder is specified by Emerson and Cumming to have $\tan\delta = .0007$ at 10 GHz.

In order to design a dielectric waveguide with a powder core, it is necessary to know how the dielectric constant of the powder varies with the packing density. This relationship was determined for each powder at 10 GHz by using the shorted waveguide technique (Ref. 1) to measure dielectric constant.

The tubing materials used were TFE teflon, polyethylene, and Corning 7740 glass (Pyrex ^{R}). The dielectric properties of these materials at 10 GHz are given by Von Hippel (Ref. 2). Although the pyrex tubes were inflexible, they were useful for making guide wavelength and attenuation measurements.

Each waveguide was made by filling a tube with powder and plugging the ends with polyfoam. The inner diameter of the tube was picked so that the HE_{11}-like mode would propagate with a wavelength significantly smaller than the free space wavelength. Coupling was achieved by inserting one end of the tube into a metal TE_{10} rectangular to TE_{11} circular waveguide transition. (The metal waveguide transition was used since the transverse fields of the TE_{11} circular mode of metal waveguide (Ref. 3) are known to be similar to those of the HE_{11} mode of a cylindrical dielectric rod.) The waveguide was centered in the coupler by a polyfoam insert. With the waveguide inserted to the proper depth (determined by trial and error), the coupling was good, and there was no detectable radiation away from the coupler and waveguide. A metal perturber placed a few mm away from the dielectric guide, outside the volume of the (HE_{11}-like) guided mode caused no change in reflected power. Finally, lossy foam was wrapped around the tube at the far end to prevent reflections.

Guide wavelength measurements were made by sliding a metal washer along the full length of the guide and observing the periodic variation in reflected power. Table 1 shows that the measured guide wavelengths were in excellent agreement with those predicted by the theory of lossless 3-region cylindrical dielectric waveguide (Ref. 4). The values of the core dielectric constant listed in Table 1 were determined by finding the density of the powder in the tube by precision weight measurement and then using the dielectric constant versus density data.

2. 94 GHZ EXPERIMENTS

94 GHz flexible dielectric waveguides were made by filling teflon tubes (18, 19, 20 AWG lightweight* electrical spaghetti) with dielectric powders. The guides were 'designed' using the theory of lossless 3-region cylindrical dielectric waveguide (Ref. 4) so that the HE_{11}-like mode would be significantly slowed. In order to use the theory, the dielectric constants of the powders were needed. We used the values measured at 10 GHz because of the difficulty of controlling the length of a powder sample sufficiently accurately to measure its dielectric constant at 94 GHz with the shorted-waveguide technique. For low-loss dielectrics we do not expect much change in dielectric constant between 10 and 94 GHz.

The powders used were Trans-Tech MCT-40 magnesium-calcium titanate, D-30 nickel-aluminum titanate, and D-8512, an improved barium tetratitanate. (Trans-Tech claims that D-8512 has lower loss than D-38 and also a smaller thermal coefficient of dielectric constant. Otherwise, we do not know the nature of the 'improvement'.) For each of these powders, all particles were less than 43 µm in size. These powders were composed of smaller particles than the ones used at 10 GHz, making it easier to pack them into the small diameter tubes used at 94 GHz.

Coupling to metal waveguide was achieved by inserting the end of the tube into a slightly flared section of WR-10 waveguide. As before, guide wavelength measurements were made by sliding a metal perturber along the length of the waveguide and observing the periodic variation in reflected power. The measured guide wavelengths agreed with the theoretical values for the HE_{11}-like mode, as shown in Table 2. For the guides represented in Table 2, there were no beats in the pattern of reflected power versus perturber position, indicating that the guides were single-mode as intended.

Attenuation measurements were made by measuring the power received with a diode detector at the far end of the waveguide. Power was coupled off the dielectric waveguide by inserting it into a flared section of metal waveguide connected to the detector. Another detector connected to a small horn was used as a movable probe to determine that there was an insignificant amount of radiation from the couplers and waveguide. Also, the power reflected back into the metal waveguide from the feed coupler was approximately -20 dB down from the incident power. Finally, guides which differed in length but were otherwise identical had losses which scaled with length. Thus, we concluded that there was very little power lost in coupling by reflection or radiation, so that the difference between the incident power and the power detected at the far end represented

CH2204-6/85/0000-0305 $01.00 © 1985 IEEE

the true dielectric waveguide loss. The loss per unit length is then this loss divided by the length of the dielectric waveguide, typically 30 cm. Table 3 gives the results of attenuation measurements on a few straight powder-filled teflon tubes.

Bending loss measurements were made using the same set-up as for attenuation measurements on straight guides. The plane of bending was perpendicular to the (vertical) plane of polarization of the HE_{11}-like mode. A problem encountered during these measurements was that the ends of the teflon tubes tended to change position inside the flared metal waveguide couplers when the tubes were bent in arcs with radius less than about 4 cm. This movement changed the quality of the coupling between the dielectric waveguide and the metal waveguides, making it difficult to obtain accurate measurements of bending losses. When the tubes were bent into circles with curvature radius greater than or equal to 4 cm, bending losses were immeasurably small.

A straightforward comparison of our bending loss observations to theory is not possible because we know of no bending loss theory that applies to 3-region guides with thin cladding, large refractive index difference between layers, and curvature radius equal to about 20 guide wavelengths. In fact, all the theories with which we are familiar assume that the refractive index differences between layers are small. Keeping these limitations in mind, we have used the theory of Kuester and Chang (Refs. 5,6) for curved dielectric rods for rough comparison. To use the theory, the rod radius and dielectric constant were chosen equal to that of the core of the actual guide and the surroundings of the rod were assumed to have a relative dielectric constant equal to one. The theoretical curvature losses were calculated for the vertically polarized LP_{10} mode, which corresponds to the unapproximated vertically polarized HE_{11} mode. Applied in this way, the theory predicted that a curvature radius less than 2 cm would be necessary for our guides to exhibit bending losses comparable to our absorptive losses.

*Teflon electrical spaghetti is available in 3 types, according to wall thickness. 'Standard wall' spaghetti has the thickest walls, followed in decreasing order of thickness by 'thin wall' and 'lightweight'.

REFERENCES

1. S. Roberts and A.R. von Hippel, 'A New Method for Measuring Dielectric Constant and Loss Tangent in the Range of Centimeter Waves', J. Appl. Phys., Vol. 17, p. 610-616, July 1946.
2. A.R. von Hippel, DIELECTRIC MATERIALS AND APPLICATIONS, John Wiley and Sons, Inc., pp. 301-370, New York, 1958.
3. S. Ramo, J.R. Whinnery, and T. Van Duzer, FIELDS AND WAVES IN COMMUNICATION ELECTRONICS, Wiley, New York, 1966, pp. 432.
4. M.H.Kuhn, 'The influence of the refractive index step due to the finite cladding of homogeneous fibers on the hybrid properties of modes,' Archiv fur Elektronik und Ubertragungstechnik, Vol. 28, pp. 393-401, October, 1974.
5. D.C.Chang and E.F. Kuester, 'Radiation and propagation of a surface-wave mode on a curved open waveguide of arbitrary cross section,' Radio Science, Vol. 11, pp. 449-457, May 1976.
6. E.F.Kuester and D.C.Chang, 'Surface-wave radiation loss from curved dielectric slabs and fibers,' IEEE Journal of Quantum Electronics, Vol. QE-11, pp. 903-907, Nov. 1975.

TABLE 1

Comparison of measured and theoretical guide wavelengths for HE_{11}-like mode of 3-region guide at X-band

Core Radius (cm)	Cladding Radius (cm)	Freq. (GHz)	Core Mat'l.	Core ϵ_r	Cladding Mat'l.	Cladding ϵ_r	Guide Wavelength Meas. (cm)	Guide Wavelength Theo. (cm)
0.33	0.45	10.000	1	7.62	A	4.52	2.05	2.06
0.25	0.35	10.000	2	13.45	A	4.52	2.30	2.19
0.26	0.30	10.000	2	11.40	B	2.08	2.88	2.86
0.26	0.30	11.311	2	11.40	B	2.08	2.14	2.09
0.30	0.40	10.940	2	13.02	C	2.25	1.38	1.32
0.32	0.47	9.794	2	12.39	C	2.25	1.71	1.65

Material 1 is nickel-aluminum titanate (Trans-Tech D-30).

Material 2 is Emerson and Cuming Ecco-flo powder.

Material A is Corning 7740 pyrex® glass.

Material B is TFE teflon.

Material C is polyethylene.

TABLE 2

Comparison of measured and theoretical guide wavelengths for HE_{11}-like mode of 3-region guide at W-band

Powder	Core Radius (mm)	Freq. (GHz)	$\epsilon_{r\,core}$	Guide Wavelength Meas. (mm)	Guide Wavelength Theo. (mm)
D-30	.43	94.78	5.60	2.48	2.42
D-8512	.43	94.72	5.45	2.55	2.47
D-8512	.48	94.75	5.83	2.21	2.10
D-8512	.53	94.10	4.79	2.06	2.24

Cladding material is TFE teflon, $\epsilon_r = 2.08$.

Cladding thickness is .15 mm.

The free space wavelength is approximately 3.2 mm.

TABLE 3

Attenuation of straight mm-wave guides

Powder	Core Radius (mm)	Freq. (GHz)	$\epsilon_{r\,core}$	Measured Guide Wavelength (mm)	Loss (dB/cm)
D-30	.43	94.78	5.60	2.48	.12
D-8512	.43	94.72	5.45	2.55	.13
D-8512	.48	94.75	5.83	2.21	.14
MCT-40	.53	94.08	4.48	2.12	.26

Cladding material is TFE teflon, $\epsilon_r = 2.08$.

Cladding thickness is .15 mm.

Loss of silver WR-10 waveguide is approximately .05 dB/cm at 94 GHz.