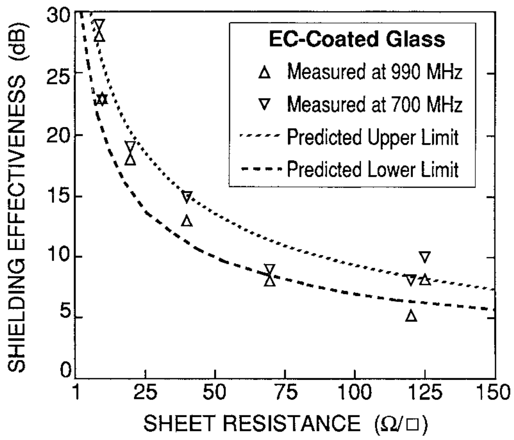

Fig. 3. Microwave shielding effectiveness of single-ply conductive glass as a function of the nominal sheet resistance; the data points are as listed in [3].

lying somewhat closer to the upper, no-substrate limit, thus validating the model and supporting some of the conclusions.

VI. Conclusion

Liao's formula [1] for the shielding effectiveness of metal-coated glass only applies to sheet resistances $R_s \lesssim 10\ \Omega/\square$ and does not take into account enhancements that may occur under "resonant" conditions. Metal-sheet reflections as evaluated in [2] dominate the loss mechanism for low-impedance films, but microwave absorption by the metal layer becomes increasingly significant for higher sheet resistance coatings. The analysis that was carried out in this paper assumes normally incident plane waves and should be applicable to any EC-coated optically transparent dielectric provided the thickness of the coating is much smaller than the skin depth. The two formulas presented in (26a) and (26b), which derive from the general expression (25), allow us to quickly assess the far-field microwave shielding performance in the sense that they yield upper and lower limits for the attenuation. For sheet resistances $R_s \lesssim \eta_0/(\sqrt{\epsilon_r}-1)$, either half-wave-thick or low-dielectric-constant substrates provide optimum shielding; for larger sheet resistances, on the contrary, quarter-wave thicknesses in conjunction with high-permittivity dielectrics result in enhanced attenuation. Substantial attenuation, however, cannot be achieved with high-resistivity coatings, irrespective of the coating's nature or the coating's design.

References

[1] S. Y. Liao, "Light transmittance and microwave attenuation of a gold-film coating on a plastic substrate," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 846–849, Oct 1975; also *Microwave Devices and Circuits*, 2nd ed. Englewood Cliffs, NJ: Prentice-Hall, 1985.

[2] R. C. Hansen and W T Pawlewicz, "Effective conductivity and microwave reflectivity of thin metallic films," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 2064–2066, Nov. 1982.

[3] H. A. Lassiter, "Low-frequency shielding effectiveness of conductive glass," *IEEE Trans Electromagn. Compat.*, vol. EM-6, no. 2, pp. 17–30, July 1964.

[4] E. I. Hawthorne, "Electromagnetic shielding with transparent coated glass," *Proc. IRE*, vol 42, pp. 548–553, Mar. 1954.

[5] S. A. Schelkunoff, *Electromagnetic Waves*. New York: Van Nostrand, 1943.

[6] C. A. Klein, "Exact formulas for the microwave shielding effectiveness of EC-coated optical windows," in *Proc. Third DoD Symp. Electromagnetic Windows*, to be published; also available from the author as Doc. No. RAY/RD/T-1184, 30 Sept 1989.

Flexible Circular Waveguides at Millimeter Wavelengths from Metallized Teflon Tubing

J. OBRZUT AND P. F. GOLDSMITH, SENIOR MEMBER, IEEE

Abstract —**Flexible waveguides for use at millimeter wavelengths have been fabricated by deposition of a metallic film onto the composite-modified inside surface of Teflon tubing. The attenuation characteristics in the range 80 to 115 GHz show losses of the order of 0.1 dB/cm. Bending, twisting, and rotating to the limit of plastic mechanical stability (curvature radius typically > 8 cm) have negligible effect on the attenuation, and bend angles ⩽ 45° produce relatively small changes in the insertion phase.**

I. Introduction

Considerable effort has been devoted to the design and characterization of dielectric waveguides for microwave frequencies, which are analogous to optical fibers. Dielectric rods of Teflon and polystyrene have been shown to operate at 71 and 74 GHz, successfully supporting propagation of hybrid modes [1]. Flexible millimeter waveguides consisting of Teflon core and Teflon cladding, as well as polyethylene multilayer waveguides, have also been demonstrated [2]. Polymeric dielectric waveguides are inexpensive, flexible, and low in weight, and are therefore attractive for a variety of practical applications. Unfortunately, they are subject to bending losses since the rod and cladding have similar dielectric constants. Recently, flexible Teflon tubing filled with a high-dielectric-constant powder of inorganic titanate salts has been fabricated, having attenuation low enough to be attractive for short-distance transmission at 10 and 94 GHz [3]. However, there are certain problems associated with dimensional imperfections and packing density irregularities, which result in scattering, reflections, and creation of multiple hybrid modes. Coupling to the TE_{11} circular metallic waveguide is also an issue.

In this paper we have focused on an alternative, which is a flexible composite consisting of thin-wall metal tubing encircled by a protective polymeric coating. Recent developments in polymer science enable materials in layered form to be tailored in both composition and size in order to meet specific requirements [4]. Upon doping, conjugated polymers can be made to exhibit semiconducting, metallic, or even superconducting properties not traditionally associated with these materials. This has resulted in a wide range of new basic research and a rich potential for applications in microelectronics and optoelectronics. We have created surface compatibility between the metal and the elastic coating by forming a film of conducting polymer on the Teflon surface. Such a modification makes Teflon accessible for metal deposition or electroplating, with good adherence at the interface. In this paper we present a brief summary of our fabrication and measurement techniques and of results obtained in the 80–115 GHz band.

Manuscript received August 23, 1989; revised October 18, 1989. This work was supported by the National Science Foundation under Grant AST 88-15406.

J. Obrzut was with the Five College Radio Astronomy Observatory, Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003. He is now with the IBM Corporation, Department 21, 1701 North Street, Endicott, NY 13760.

P. F. Goldsmith is with the Five College Radio Astronomy Observatory, Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003, and with the Millitech Corporation, South Deerfield, MA 01373.

IEEE Log Number 8933005.

0018-9480/90/0300-0324$01.00

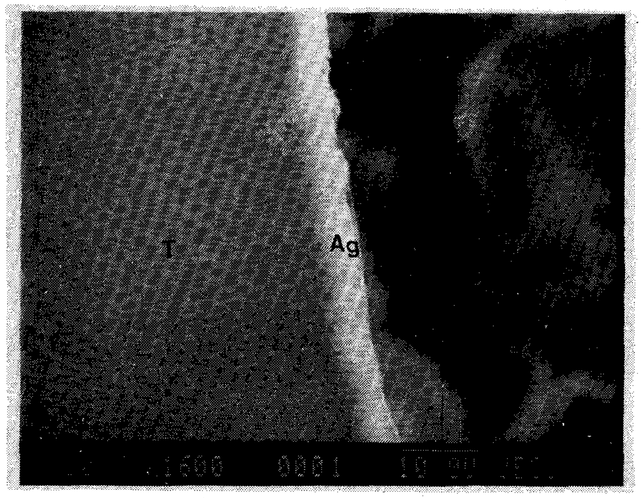

Fig. 1. Cross section of silver-plated waveguide. The electroplated silver layer, indicated by Ag, appears bright, while the unprocessed Teflon, located to the left and indicated by T, appears much darker. The defluorinated Teflon layer between them is very thin and is hardly visible on this photograph.

II. Fabrication

Tubing of poly(tetrafluoroethylene) was obtained from a standard electronic supplier [5]. Modification [6] of the surface inside the Teflon tubing before metallizing was accomplished by filling it with a potassium complex of benzoin dianion, as described in [7]. The solution of the potassium complex was prepared by mixing 2 g of potassium tert-butoxide dissolved in 40 ml of dimethylsulfoxide, with 0.5 g of benzoin dissolved in 10 ml of dimethylsulfoxide. The dark-purple solution of the potassium complex was transferred into the Teflon tubing which had been equilibrated to a temperature of 55°C. The reaction was allowed to proceed at the temperature 50–55°C for 8 hours, after which the complex was removed; the tubing was then washed with tetrahydrofurane and water and dried under an inert argon atmosphere. The process which takes place at the polymer surface involves electron transfer from benzoin-dianion to poly(tetrafluoroethylene) with loss of fluoride (defluorination). This produces a metallic-gold-colored thin film of conducting conjugated polymer analogous to that of polyacetylene or poly(phenylenevinylene) [4], [8]. In contrast to Teflon, the surface after modification is hydrophilic-like, and acquires the desired adherence to metals. The formation of a very low resistance metallic film was accomplished by electroless plating of platinum, copper, or silver using electroless baths of nominal composition [9]–[11]. The variation of plated metals had no significant effect on waveguide properties, although deposition of multimetal layers such as platinum and then silver resulted in slightly lower attenuation. From a practical viewpoint we focused on silver-plated waveguides which consist typically of a 2–3 μm electroless silver layer deposited onto a 0.1–0.2 μm thick modified Teflon surface. A cross section through the waveguide is shown in Fig. 1.

III. Measurements

Measurements of the attenuation of the flexible millimeter waveguide were made over the frequency range of 80 to 115 GHz. The output of a swept microwave source (Hewlett Packard Model 83550A) covering approximately 13 to 19 GHz was fed to an active frequency doubler (Avantek Model AMT 401X2) having a power output of about 50 mW. The 27 to 38 GHz output of the doubler was fed to a frequency tripler (Millitech Model MUT-10) having an output power of approximately 0.5 mW. The signal in the 81 to 114 GHz range was detected by a biased Schottky diode using an adapted mixer of the type described in [12]. This construction, with the 27.5 kHz modulation of the Hewlett Packard HP 8757A measurement system, provides a dynamic range exceeding 35 dB, beyond the normal attenuation of about 15 dB inserted to guarantee good detector linearity.

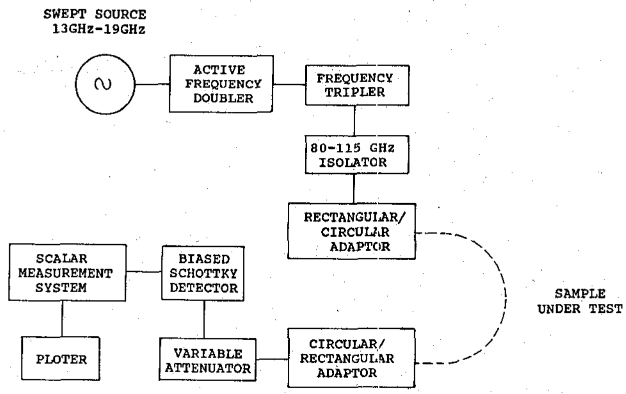

Fig. 2. Schematic of instrumental setup for attenuation measurements in the range 80–115 GHz using cascaded frequency multipliers.

A block diagram of the insertion loss measurement system is shown in Fig. 2. The attenuation of each sample was determined by first normalizing to the power transmitted through a pair of TE_{10} (rectangular waveguide) to TE_{11} (circular waveguide) transitions. The additional loss of the flexible millimeter waveguide was determined in general by inserting the sample being evaluated into the circular ends of the adapters. A small discontinuity between the adapters and inserted Teflon tubing resulted in an additional loss and reflection, which were, however, quite small and also were very reproducible. The phase measurements were carried out using a HP 8510 network analyzer with a frequency extender covering the frequency range of 93 to 95 GHz.

A fixture to hold the flexible waveguide which included a tapered circular waveguide section was also fabricated. One end was made with a standard UG387/U flange pattern and circular waveguide 3.18 mm in diameter to match the diameter of the round end of the circular-to-rectangular adapters. The circular waveguide in the fixture was tapered to the 2.7 mm inside diameter of the flexible waveguide, and provided a step increase in the outer diameter which allowed accurate insertion of the Teflon tubing.

IV. Results and Discussion

A number of samples of differing lengths were prepared according to the procedure given in Section II. All waveguides had inside diameter equal to 0.27 cm, which corresponds to a cutoff frequency for the TE_{11} mode of 65.9 GHz. The cutoff for the next higher mode (TE_{21}) is 109.2 GHz. The insertion loss was measured using the setup shown in Fig. 2 and the results, along with measurements of dc resistance, are summarized in Table I.

The samples exhibit significant variation of insertion loss with frequency, but as shown in Fig. 3 this behavior is not a monotonic function of frequency, and it is not consistent from sample to sample. It may be a result of processing variations producing differing waveguide surfaces. All measurements are consistent with a loss of 0.14 dB/cm over the 80 to 115 GHz range. This value is comparable to those obtained for solid dielectric waveguides by Jablonski [1] extrapolated to the appropriately higher frequency. The attenuation for the flexible metallic waveguide is

TABLE I
INSERTION LOSS MEASUREMENTS FOR FLEXIBLE WAVEGUIDE SAMPLES IN 80–115 GHz FREQUENCY RANGE

Length (cm)	DC Resistance (Ω)	Loss (dB)	Average Loss (dB/cm)
14	1.5	1.75 ± 0.25	0.15
26	2.5	3.5 ± 1	0.13
40	6.9	6.0 ± 2	0.13

All waveguide samples have inner diameter equal to 0.27 cm.
The range of insertion loss for each sample is the variation with frequency.

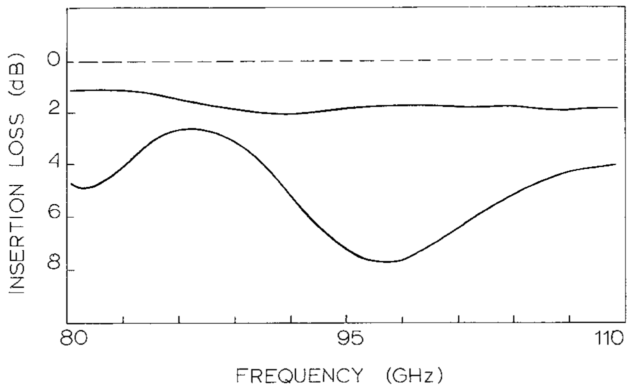

Fig. 3. Measured insertion loss as a function of frequency of two samples of flexible circular waveguide. The upper curve is for the 14-cm-long sample and the lower curve is for the 40-cm-long sample.

almost the same as that obtained by Bruno and Bridges [3] for powdered-core dielectric waveguides. While considerably higher than the theoretical values for rectangular silver waveguide, the measured values are only about factor of 2 greater than typically measured for rigid waveguide.

The metallic layer shown in Fig. 1 has a thickness between 3 and 5 μm, considerably larger than the skin depth in a good conductor such as silver ($\rho = 1.6 \times 10^{-6}$ $\Omega \cdot$cm). The dc resistance measurements yield values for the ratio of the thickness of the conducting layer to its resistivity, t/ρ, in the range 7–12, which with this nominal value of resistivity gives an effective thickness of 0.1–0.2 μm. It thus seems likely that the effective resistivity is considerably higher than the value given above for silver. Even with a much higher value of resistivity, the skin depth will be smaller than or comparable to the thickness of the conducting layer, so we apply the standard formula for attenuation in a circular waveguide [13], which for the dimensions of the samples here yields a theoretical loss of $0.016[\rho/1.6 \times 10^{-6}\ \Omega \cdot \text{cm}]^{0.5}$ dB/cm. The average measured loss from Table I is a factor of 8.6 larger than that expected if the resistivity were that of silver, so we infer an effective resistivity that is greater by a factor of approximately 70. Using this value in the relation for t/ρ, we find the effective thickness to lie in the range 8–14 μm. The fact that this is larger than that indicated by the visual appearance of the conducting layer suggests that a portion of the millimeter-wavelength loss is due to surface roughness, an effect seen in rigid metallic waveguides as well [14], [15]. If a factor of 2 excess loss is assigned to surface effects, the effective thickness of the conducting layer is close to 3 μm, entirely consistent with that found from the optical photograph.

We determined the effects of bending the waveguides by moving the attenuator and detector in Fig. 2 relative to the source. For the 26 cm sample, small bends ($\leqslant 30°$) produced quite small changes in the insertion loss. A bend of 90° with an 8 cm radius of curvature produced a change in the insertion loss of < 1 dB across the measurement range. This change may be due to deformation of the waveguide and production of cross-polarized energy. There was not a major difference in the loss as a function of the plane of the bend of the waveguide.

The effect of bending on the phase of the 26 cm sample was determined in the 93 to 95 GHz range by measuring the change in the insertion phase for different bend angles. For angles $\leqslant 45°$ the change in phase was less than 15°. The change increased rapidly for larger bend angles, and was 65°–80° for angles of 90° and 180°. The phase change is plausibly a result of deformation in the guide cross section, but was not critically dependent on the plane in which the waveguide was bent.

V. SUMMARY

We have presented a novel method of fabricating flexible TE_{11}-mode circular millimeter waveguides from Teflon tubing. The attenuation in the 80–115 GHz range is approximately 0.1 dB/cm and appears highly stable with respect to a bending radius of curvature as small as 8 cm. We expect that the insertion loss will be reduced by better surface processing techniques. The change in phase is relatively modest for bend angles $\leqslant 45°$. This technology should prove very useful for a wide range of applications, including scanning antennas and near-field measurement systems, as well as general laboratory use.

ACKNOWLEDGMENT

The authors thank the Microwave Remote Sensing Laboratory of the Department of Electrical and Computer Engineering, University of Massachusetts, for making their network analyzer available for phase measurements. This is contribution #713 of the Five College Radio Astronomy Observatory and Five College Astronomy Department.

REFERENCES

[1] D. Jablonski, "Attenuation characteristics of circular dielectric waveguide at millimeter wavelengths," *IEEE Trans Microwave Theory Tech.*, vol MTT-26, pp. 667–671, Sept. 1978.
[2] S. Shindo and I. Ohtomo, "A coaxial type dielectric waveguide for 100 GHz band," *Tech Rep. IECE Japan*, MW75-105, pp 75–80, 1975.
[3] W. M. Bruno and W. B. Bridges, "Flexible dielectric waveguides with powder cores," *IEEE Trans Microwave Theory Tech*, vol. 36, pp 882–890, May 1988.
[4] G. B. Street and T. C. Clarke "Conducting polymers: A review of recent work," *IBM J. Res. Develop.*, vol. 25, pp. 51–57, Jan 1981
[5] Commercial Plastics/Du Pont Teflon from Penntube Products, Clifton Heights, PA. No. 7357 AY.
[6] K. Yoshino *et al.*, "A conducting polymer from Teflon," *Japanese J Appl. Phys.*, vol. 21, pp. L301–L302, 1982.
[7] C. A. Castello and T. J. McCarthy, "Surface selective introduction of specific functionalities onto poly(tetrafluoroethylene)," *Macromolecules*, vol. 20, pp 2819–2828, 1987.
[8] D. J. Barker, D. M. Brewis, R. H. Dahm, and L R J Hoy, "Study of the intercalated carbon formed by electrochemical reduction of poly-(tetrafluoroethylene)," *Polymer*, vol. 19, pp. 856–857, 1978.
[9] R Junginger and G. Elsner, "On the texture of electroless copper films," *J. Electrochem. Soc*, vol 135, pp. 2304–2308, Sept 1988
[10] R. R. Bair and A K. Graham, in *Modern Electroplating*, F. A. Lovenheim, Ed New York: Wiley, 1963.
[11] R. C. Sausa and A Gupta, "Laser decomposition of platinum metallo-organic films for electroless copper plating," *J Electrochem. Soc.*, vol. 134, pp. 2707–2713, Nov 1987
[12] C. R Predmore, A. V. Raisanen, J. F Marrero, N. R. Erickson, and P F. Goldsmith, "A broadband, ultra low-noise Schottky mixer receiver

from 80 to 115 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 498–507, 1984.
[13] T. Moreno *Microwave Transmission Design Data.* New York: Dover, 1958, p. 134.
[14] F. A. Benson and D. H. Steven, "Rectangular-waveguide attenuation at millimetre wavelengths," *Proc. Inst. Elec. Eng.*, vol. 110, no. 6, pp. 1008–1014, June 1963.
[15] F. J. Tischer, "Experimental attenuation of rectangular waveguides at millimeter wavelengths," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 31–37, Jan. 1979.

Experimental Evaluation of Existing CAD Models for Microstrip Dispersion

R. A. YORK AND R. C. COMPTON, MEMBER, IEEE

Abstract —**Microstrip dispersion measurements covering a variety of different substrate materials and line impedances were carried out using the gap-coupled resonator pair method. The results were compared against nine microstrip dispersion models. The results indicate two models that are consistently accurate and are therefore recommended for CAD applications.**

I. INTRODUCTION

Despite the obvious need, there have been relatively few published measurements of dispersion which have been complete enough to form the basis of a thorough evaluation of the different models. A collection of published dispersion measurements has been compiled by Atwater and compared with various models [1]. However, the errors introduced in extracting data from these published curves are comparable to the errors in the models themselves. With the increasing importance and use of CAD programs, it is necessary to choose from among these models. We have made many measurements of microstrip dispersion, over the range of 1–18 GHz, covering a variety of substrate materials and line impedances. Measurements were made (Fig. 1) using the method of gap-coupled resonator pairs [2].

For convenience, the CAD models chosen for evaluation are designated as follows: Jansen [3], Kobayashi [4], Yamashita [5], Hammerstad [6], Pramanick [7], Getsinger [8], Edwards [2], Carlin [9], and Schneider [10].

II. EXPERIMENTAL RESULTS

Typical measurement results are shown in Fig. 2. The error bars in this figure were calculated using a measurement uncertainty of ± 1 MHz in frequency and ± 0.05 mm in length, corresponding to about 0.8 percent, or ± 0.05 in the measured permittivity. Also given for comparison are calculated effective permittivities using the analysis of Denlinger [11]. In order to compare the various models, a figure of merit was assigned as the average percent difference between the measured data and calculated result.

Extrapolating the measured dispersion curves to zero frequency gave the static effective permittivity $\epsilon_{\mathrm{eff}}(0)$, from which

Manuscript received August 24, 1989; revised October 18, 1989.
The authors are with the School of Electrical Engineering, Cornell University, Ithaca, NY 14853.
IEEE Log Number 8933006.

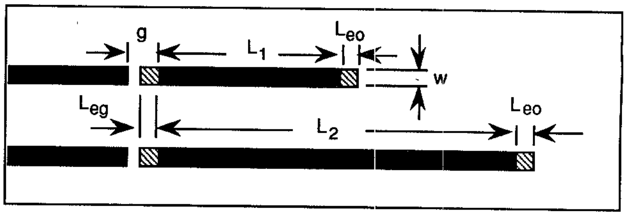

Fig. 1. Gap resonator pair for dispersion measurements. By measuring the resonant frequency of the two resonators end effects can be canceled.

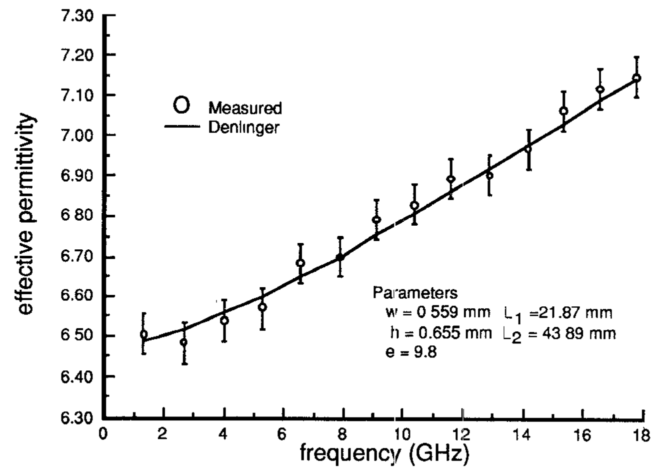

Fig. 2. Typical results of measurement, including theoretical results for comparison. The figure of merit for the Denlinger model in this example is 0.34 percent deviation.

the substrate dielectric constant could be determined. This was important since the substrate permittivity was known to deviate from the manufacturer's specifications.

In all, 18 separate resonator pairs were fabricated and measured, encompassing eight different soft substrate materials and three different line impedances. The physical specifications of each of these are given in Table I. The data were gathered in each case using an HP 8510A and an HP 5343 frequency counter, and the expected experimental error as mentioned earlier was calculated to be $\simeq 0.8$ percent. The models which give the most consistently accurate results are the Jansen [3] and Kobayashi [4] models. In every instance they are within the limits of experimental uncertainty. They yield rms errors of 0.71 percent and 0.73 percent respectively, which are significantly lower than the rms errors of 2.3 percent and 2.5 percent presented in [1]. The larger error values in [1] include errors introduced in retrieving data graphically from published graphs. The Edwards model [2] is fairly consistent also, while the rest show varying accuracy between measurements. A more thorough discussion of the various dispersion models and measurement techniques has been given recently in [12].

III. CONCLUSIONS

Several dispersion models have been evaluated in order to select the most promising for inclusion in CAD programs. It was found that the Kirschning and Jansen [3] and Kobayashi [4]

0018-9480/90/0300-0327$01.00 ©1990 IEEE