(NASA-CR-175423) NUMERICAL METHODS FOR ANALYZING ELECTROMAGNETIC SCATTERING Semiannual Report, 25 Sep. 1983 - 24 Mar. 1984 (Illinois Univ.) 21 p HC A02/MF A01 CSCL 20N G3/32

N84-19620

Unclas 11934

Semi-Annual Report for

NUMERICAL METHODS FOR ANALYZING ELECTROMAGNETIC SCATTERING

September 25, 1983 to March 24, 1984

Submitted to

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National Aeronautics and Space Administration
Lewis Research Center (MS 54-3)
Cleveland, OH 44113

Grant No. NAG-3-475

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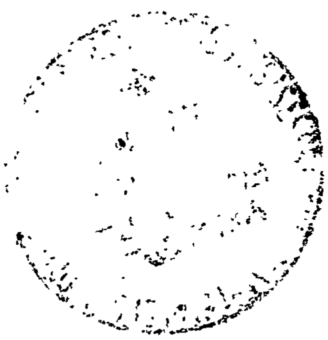
March 23, 1984



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I. INTRODUCTION

The research grant NAG 3-475 entitled "Numerical Methods for Analyzing Electromagnetic Scattering" was awarded to the University of Illinois by NASA-Lewis Research Center on September 28, 1983. Dr. Y. C. Cho of NASA's Microwave Amplifier Section is the Technical Officer, and Mr. Boyd M. Bane is the contracting officer. The total amount of funds received by the University is

$22,385 + $52,600 = $74,985

to cover the period from

September 25, 1983 to November 25, 1984 (14 months).

This report is the first semi-annual report for the period September 25, 1983 to March 24, 1984.

II. TECHNICAL PERSONNEL

S. W. Lee	Professor of Electrical and Computer Engineering
Y. T. Lo	Professor of Electrical and Computer Engineering
S. L. Chuang	Assistant Professor of Electrical and Computer Engineering
C. S. Lee	Research Assistant of the Department of Electrical and Computer Engineering

III. PRESENTATION AND PUBLICATIONS

1. Professors S. W. Lee and Y. T. Lo traveled to NASA Lewis on November 1, 1983 to present a talk entitled "Electromagnetic Scattering by Cylinders and Spheres." Viewgraphs of the presentation are published as Electromagnetic Laboratory Report 83-1 under the same title.

2. S. L. Chuang, S. W. Lee and Y. C. Cho, "Approximate Solutions for Reflection from an Open-ended Waveguide," 1984 IEEE AP-S/URSI Symposium, Boston, MA, June 25-28, 1984.

3. C. S. Lee, S. L. Chuang and S. W. Lee, "Wave Attenuation and Mode Dispersion in a Waveguide Coated with Lossy Dielectric Material," paper to be presented in the Sixth Annual Workshop of the Industrial Affiliates Program on Communication, Antennas, and Propagation (CAP), Urbana-Champaign, IL, April 5-6, 1984.

IV. TECHNICAL PROGRESS

In the past six-month period, we studied the wave propagation inside a cylindrical waveguide coated with lossy dielectric material due to the incidence of a plane wave at the open end of the guide (Figure 1).

The first step for this problem is to obtain the propagation constants of the normal modes in the lossy waveguide. Before we select any practical material for the lossy dielectric, we have investigated the general properties of the normal mode propagation.

The characteristic equation for the propagation constant of a normal mode in the lossy cylindrical waveguide can be derived by matching the boundary conditions on the conducting surface and the interface between the lossy dielectric and the air region in the cylinder. Then this characteristic equation is solved numerically. In the cylindrically symmetric geometry, mode coupling is largest between TE and TM modes with the same mode indices, e.g., TE_{11} and TM_{11}. Though the normal mode in this case is no longer pure TE or TM, it is closer to one of two modes when the thickness

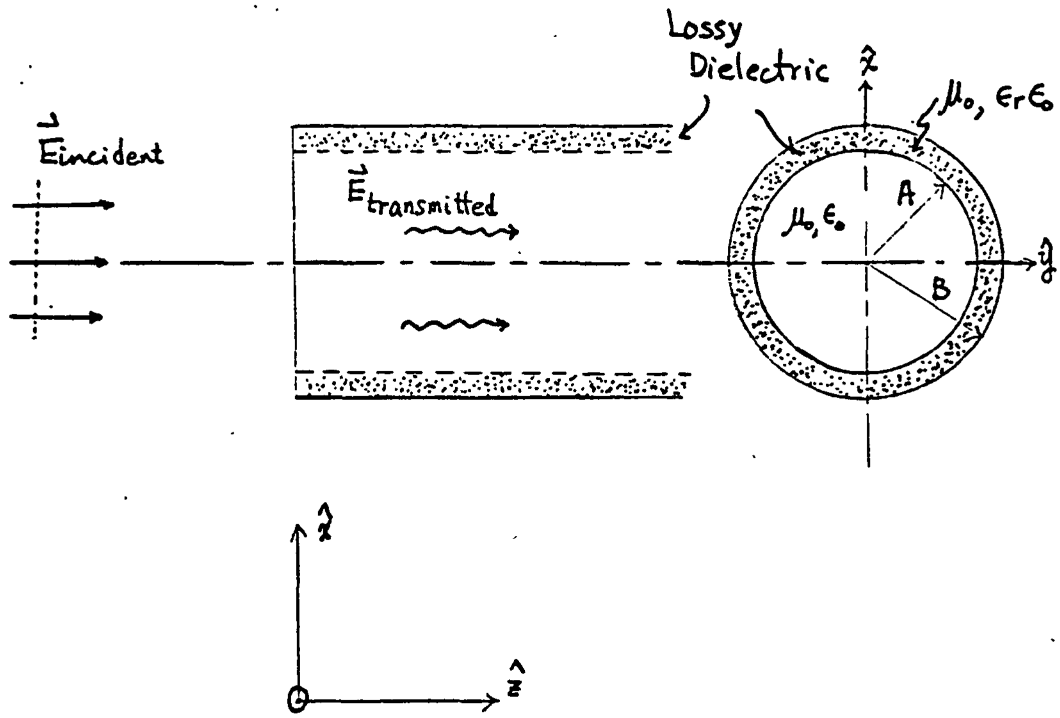

Fig. 1. An open-ended cylinder illuminated by an incident plane wave.

of the dielectric layer is small. We call this mode "quasi" TE or TM mode, and will use the same notation as in the unperturbed waveguide.

Figures 2 and 3 show the real and imaginary parts of the propagation constants of the TE_{11} and TM_{11} modes as a function of frequency in a waveguide coated with a thin dielectric material. The exact numerical solutions are compared with the results based on the perturbation theory which we have applied to derive the attenuation constant following Harrington*. We can see that the perturbation theory is valid only at the low frequency region even though the thickness of the dielectric layer is small. At the high frequency region, the TE_{11} mode shows much higher attenuation than the TM_{11} mode. This is due to the fact that the TE_{11} modal field moves closer to the surface of the cylinder than the TM_{11} mode as frequency increases.

Figures 4 and 5 show the attenuation constants as a function of the complex dielectric constant ε_r of the lossy dielectric material. We observe two interesting features in these graphs. First, there is a clear "resonance" effect of the imaginary part ε_r^I of ε_r on the attenuation constant when the real part ε_r^R of ε_r is small ($\lesssim 1.5$). Second, a smaller ε_r^R gives a larger attenuation constant except for those with a "dielectric resonance." To understand the results, consider: The attenuation constant to be proportional to the power loss within the dielectric layer, which is related to ε_r^I and the magnitude of the electric field within the dielectric layer. The angular E field E_ϕ is small in the dielectric region when the dielectric layer is thin, because the tangential E field vanishes on the surface of a perfect conductor. Thus the radial E field E_ρ is responsible

*R. F. Harrington, Time-Harmonic Electromagnetic Fields, McGraw-Hill, New York, 1961.

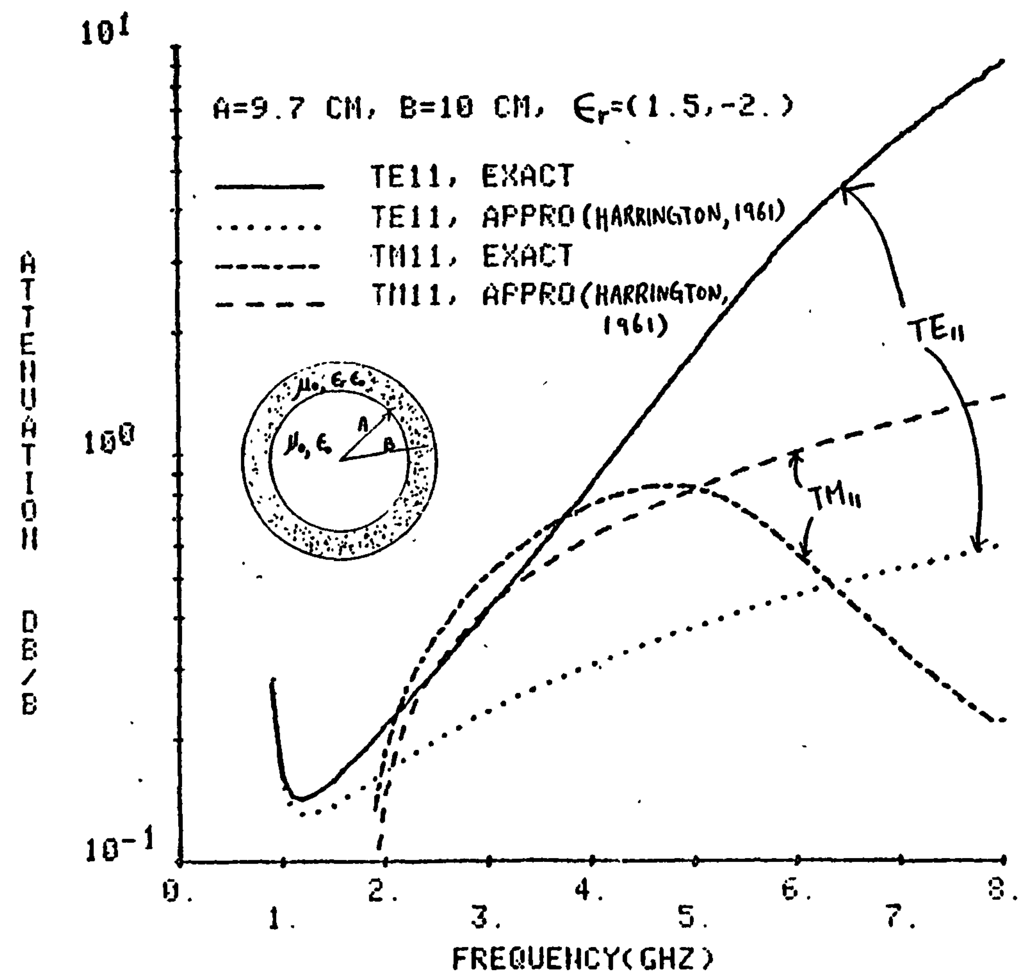

Figure 2. Attenuation constant with variation of frequency.

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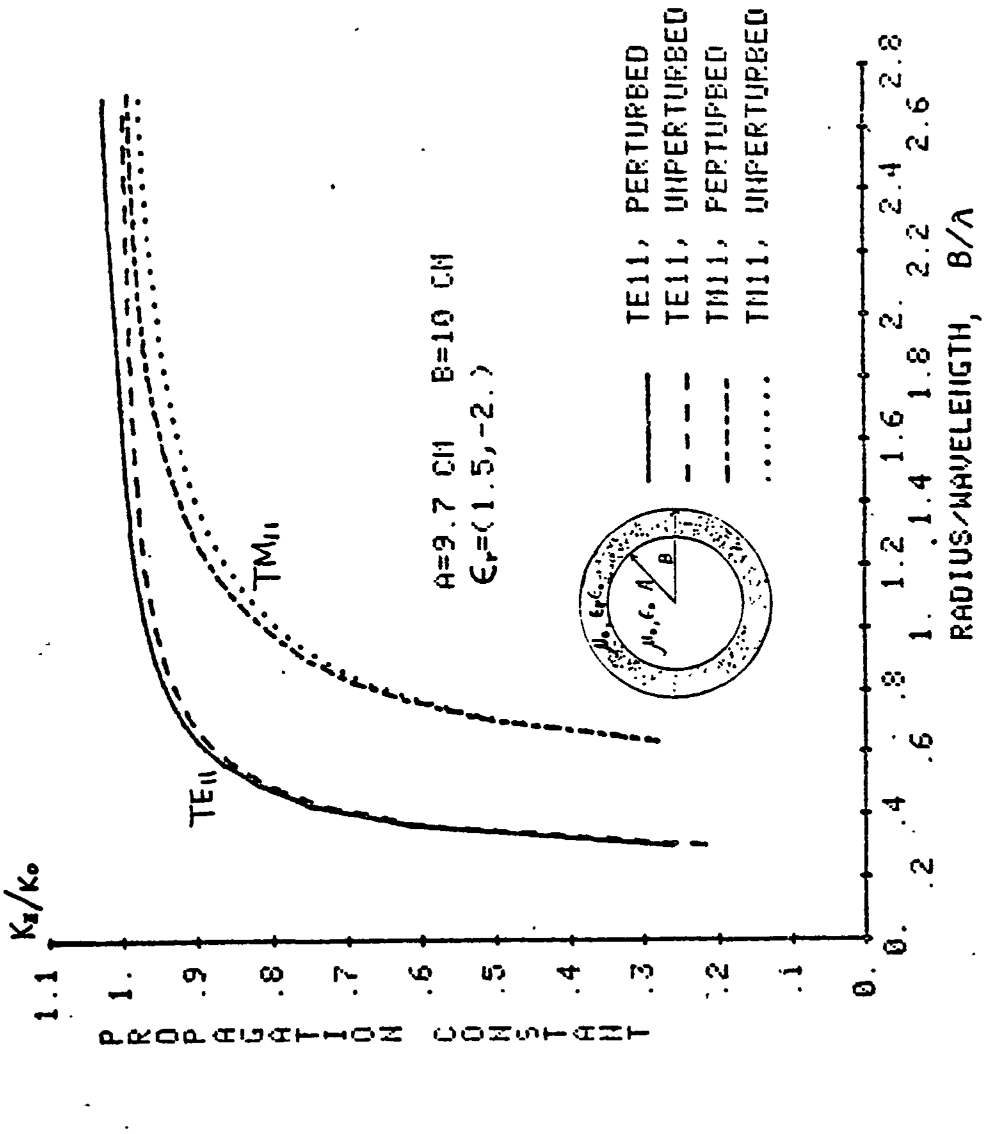

Figure 3. Real part of propagation constant.

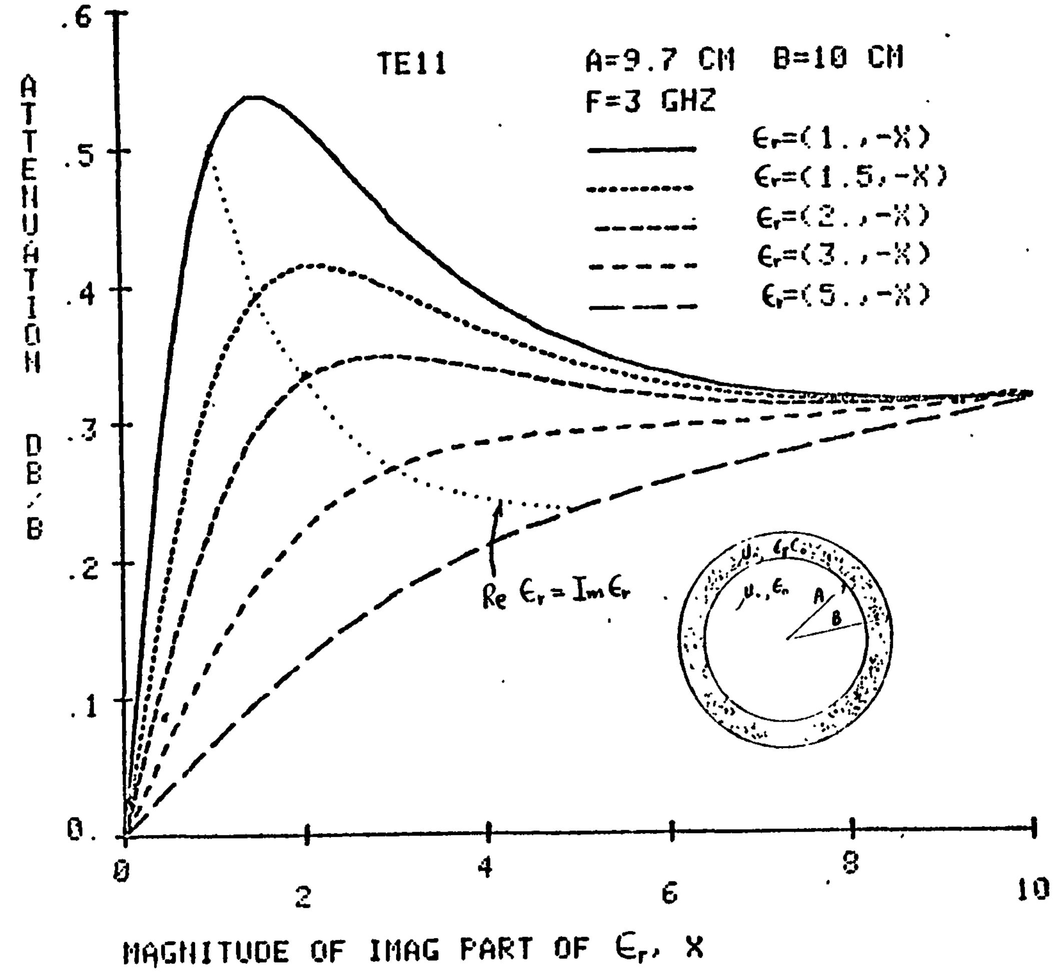

Figure 4. Attenuation constant with variation of $\varepsilon_r(TE_{11})$.

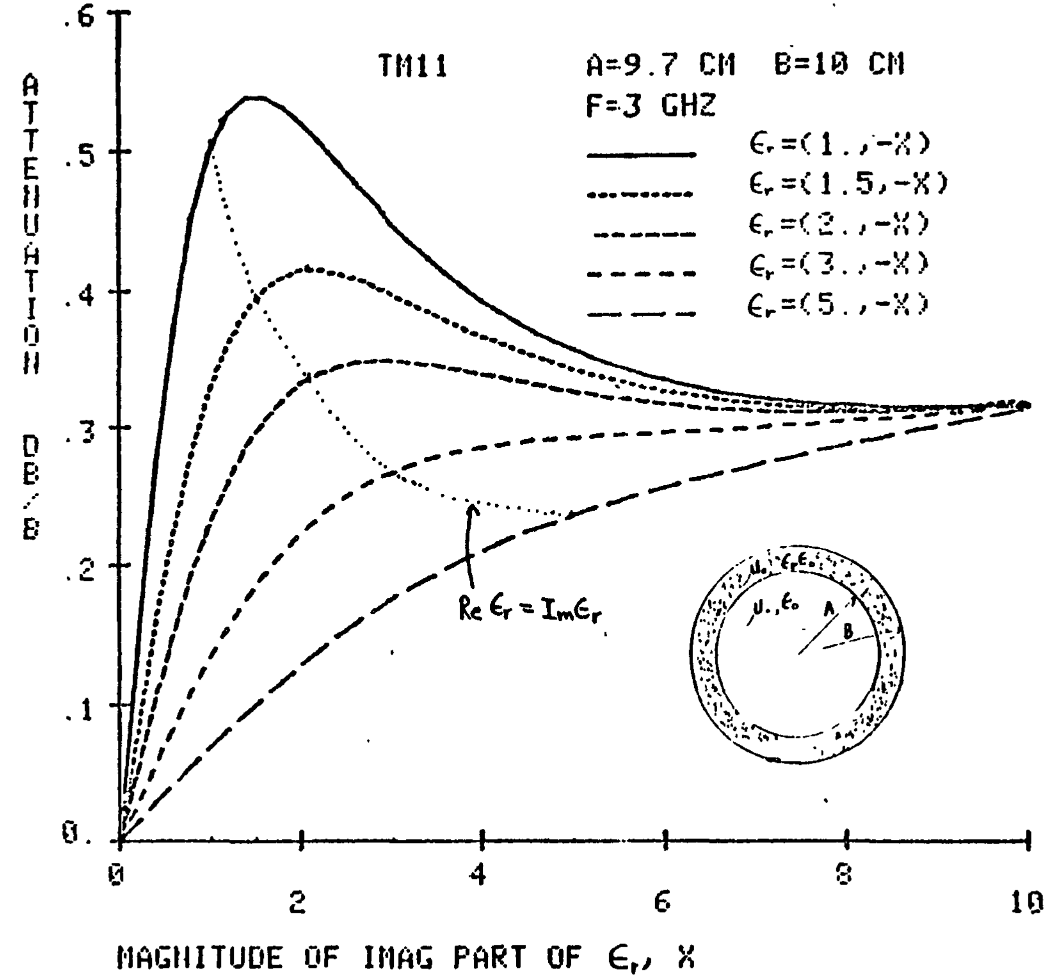

Figure 5. Attenuation constant with variation of $\varepsilon_r(TM_{11})$.

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for most of the power loss when $|\varepsilon_r|$ is not too large. Since E_ρ is inversely proportional to $|\varepsilon_r|$ at the dielectric region, increasing the real part of ε_r actually decreases the power loss, and subsequently, the attenuation constant. Since the power loss is also proportional to ε_r^I, the attenuation constant becomes saturated as ε_r^I becomes very large because those two effects of ε_r^I on the attenuation constant are about the same.

From the above results, it is natural to choose the lossy dielectric material with a small ε_r^R and a large ε_r^I (i.e., a large loss tangent) for large attenuation within the waveguide. Plastics are in this category* and three materials are chosen for further analysis (Table 1). Figures 6, 7, and 8 show the power attenuation of the transmitted wave from the normally incident plane wave with a unit power on the aperture. In order to calculate the transmitted power, we use the Kirchhoff's approximation to find the equivalent aperture source at the waveguide opening from the incident field. Even though only two modes (TE_{11} and TE_{12}) are propagating in this particular geometry, 85% of the incident power is transmitted. There are two interesting features to be observed. Most of the power is carried by the dominant mode (TE_{11}) and the attenuation constant of the dominant mode is usually larger than that of the higher mode. As those two modes propagate through the waveguide, eventually the higher mode will carry most of the power, but when this happens the total power has already decayed to a small fraction of the initialpower at $z = 0$.

When the dielectric layer is thick, the behavior of the propagation constant is different from the one for the thin dielectric layer. These features are shown in Figures 9, 10, 11 and 12. We observe the following

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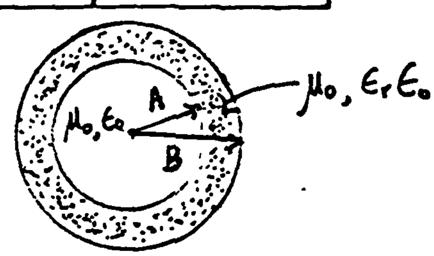
*A. R. Von Hippel, ed., Dielectric Materials and Applications, Technology Press, M.I.T., Cambridge, Mass., 1954.

Table 1. The dielectric constants of the lossy dielectric materials and the propagation constants of TE_{11} and TE_{12} modes when these materials are used in the waveguide.

Figure	6	7	8
Material	Polystyrene 70% Carbon 30%	Catalin 700 base	Pyralin
*Real ϵ_r	9.1	4.74	3.74
*Imag ϵ_r	-2.275	-0.7252	-0.6171
Real $K_z \times B$ TE_{11}	6.1321	6.1059	6.0960
Imag $K_z \times B$ TE_{11}	-1.0388×10^{-2}	-6.1856×10^{-3}	-7.2436×10^{-3}
Real $K_z \times B$ TE_{12}	3.3726	3.3554	3.3513
Imag $K_z \times B$ TE_{12}	-9.2734×10^{-2}	-2.9211×10^{-3}	-2.6319×10^{-3}

A=9.7 cm, B=10 cm

*A. R. Von Hippel, ed., Dielectric Materials and Applications, Technology Press, M.I.T., Cambridge, Mass., 1954.



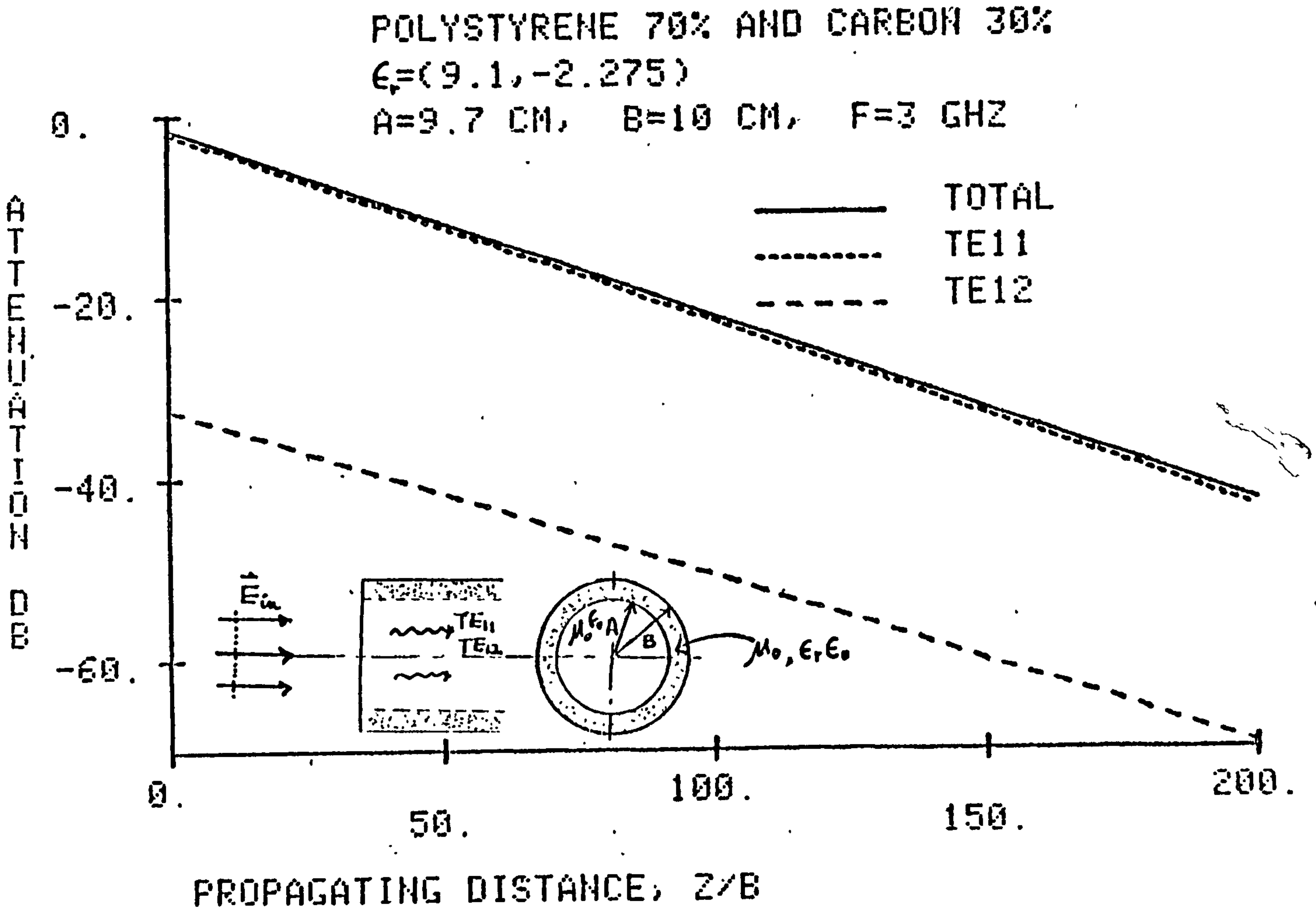


Figure 6. Attenuation along the waveguide from normal incident wave (polystyrene 70% and carbon 30%).

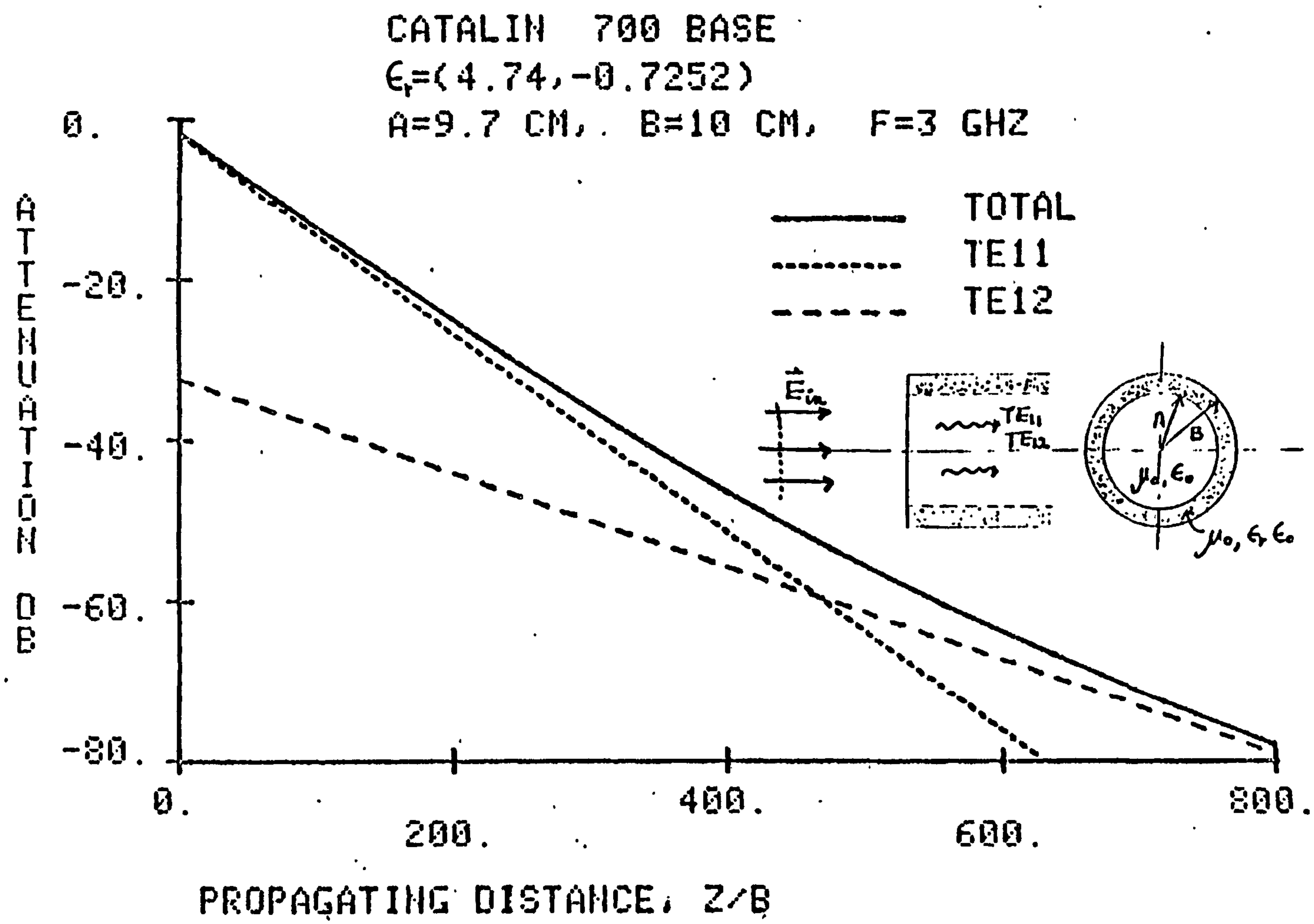


Figure 7. Attenuation along the waveguide from normal incident wave (catalin 700 base).

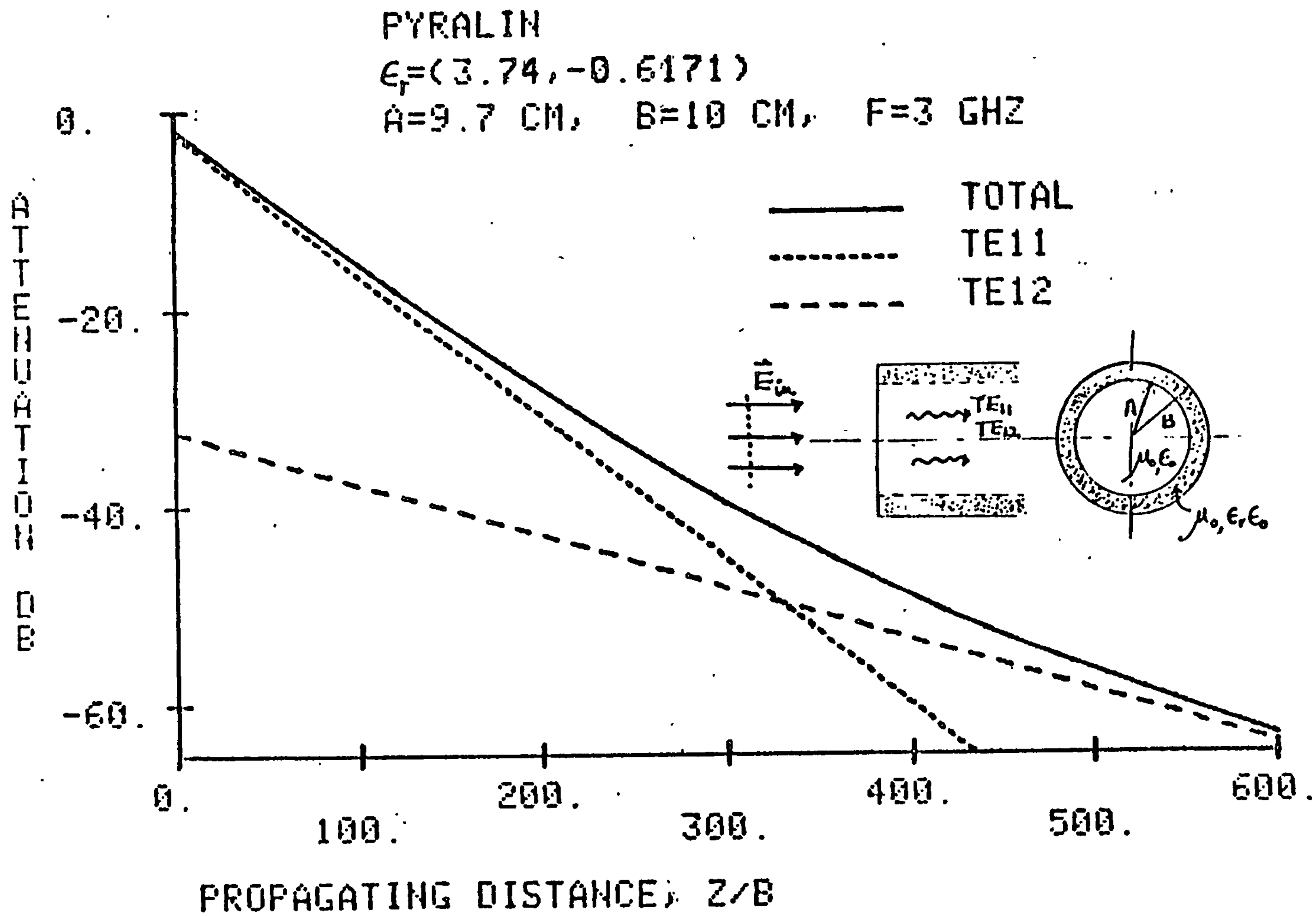


Figure 8. Attenuation along the waveguide from normal incident wave (pyralin).

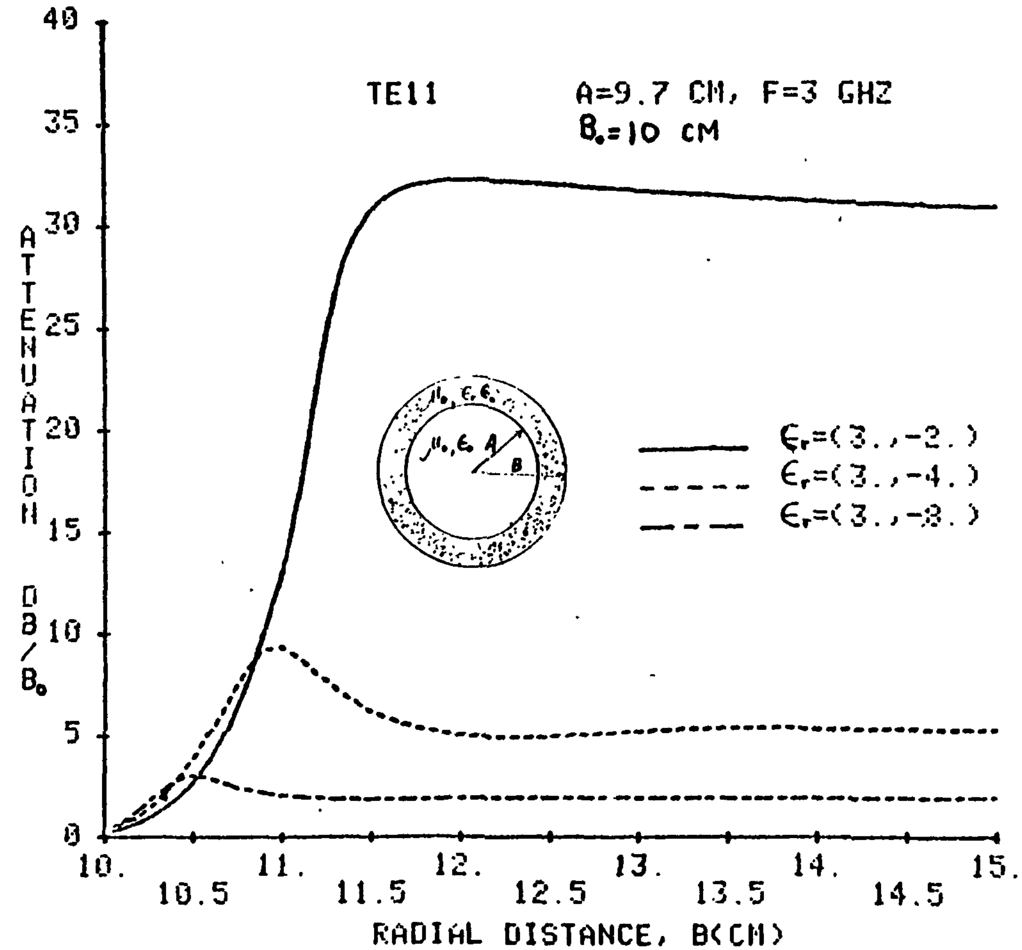


Figure 9. Attenuation constant with variation of $B(TE_{11}, \epsilon_r^R = 3)$.

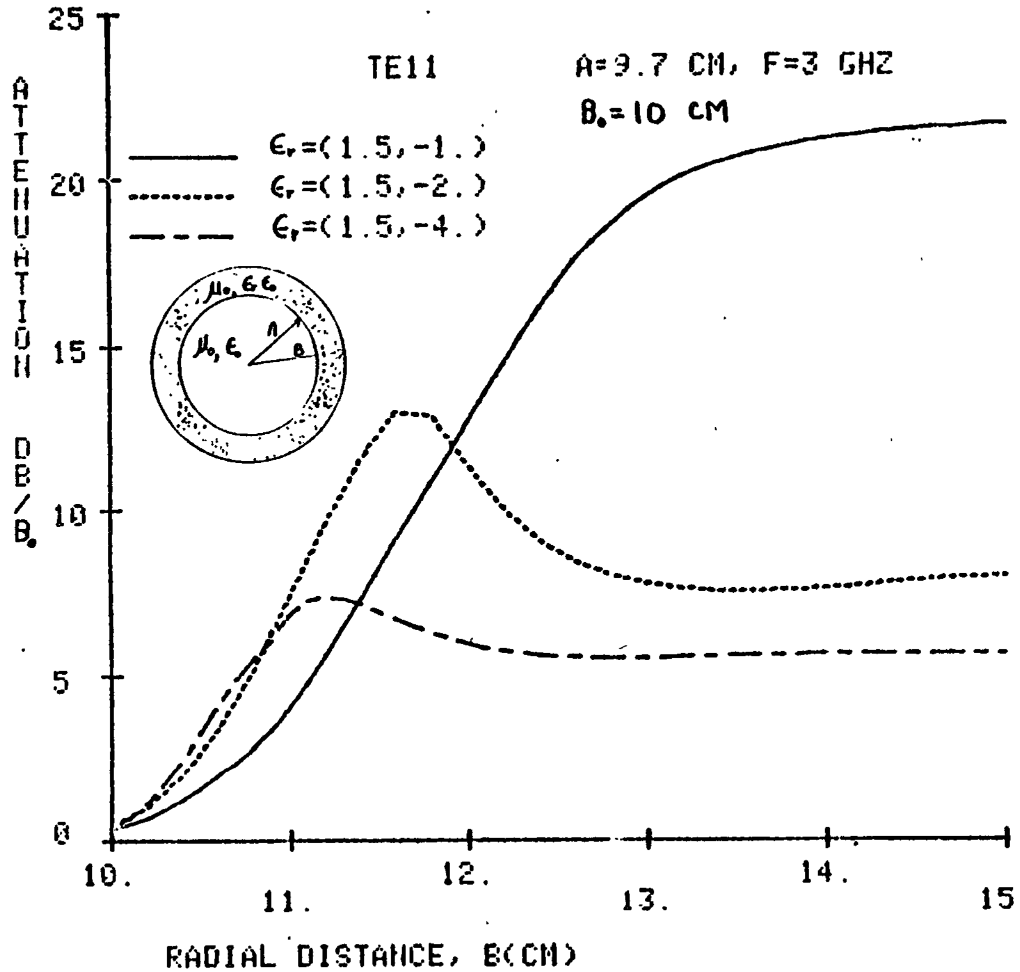


Figure 10. Attenuation constant with variation of B(TE_{11}, $\varepsilon_r^R = 1.5$).

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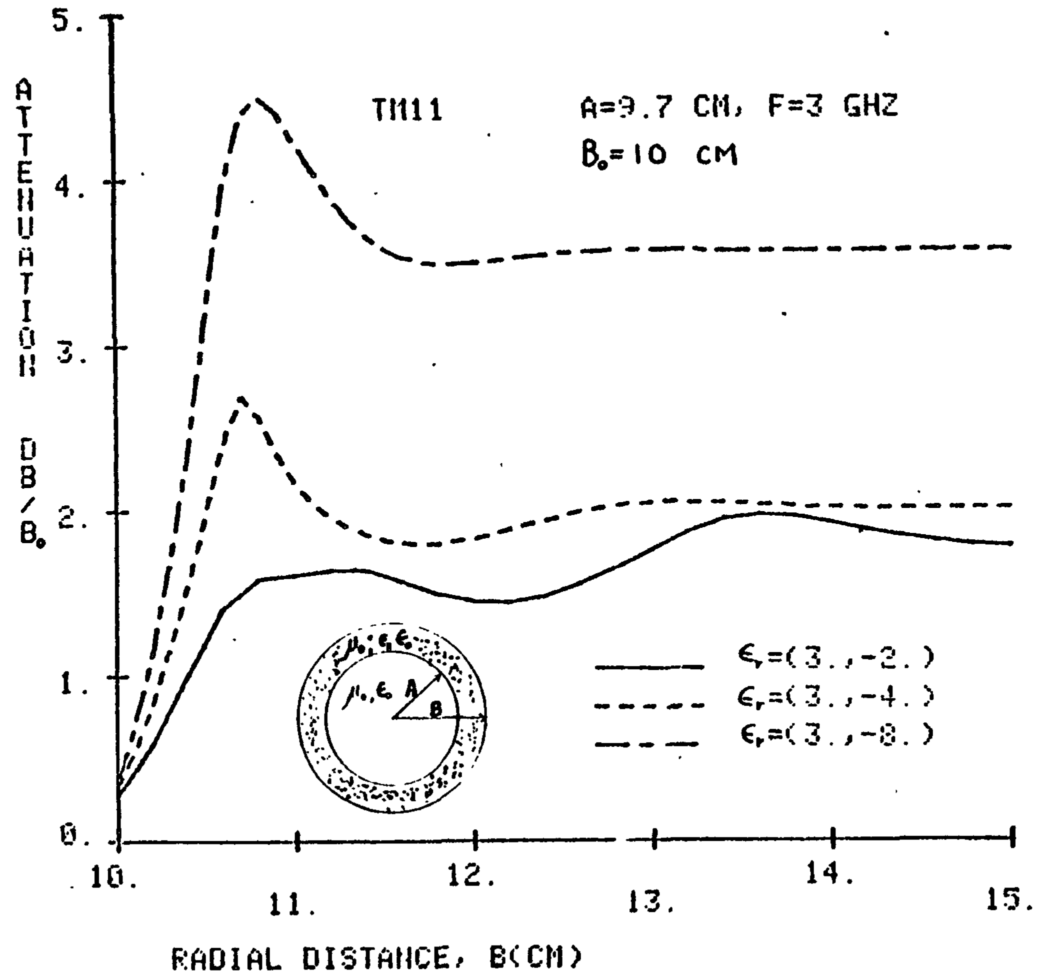

Figure 11. Attenuation constant with variation of B(TM_{11},ε_r^R = 3).

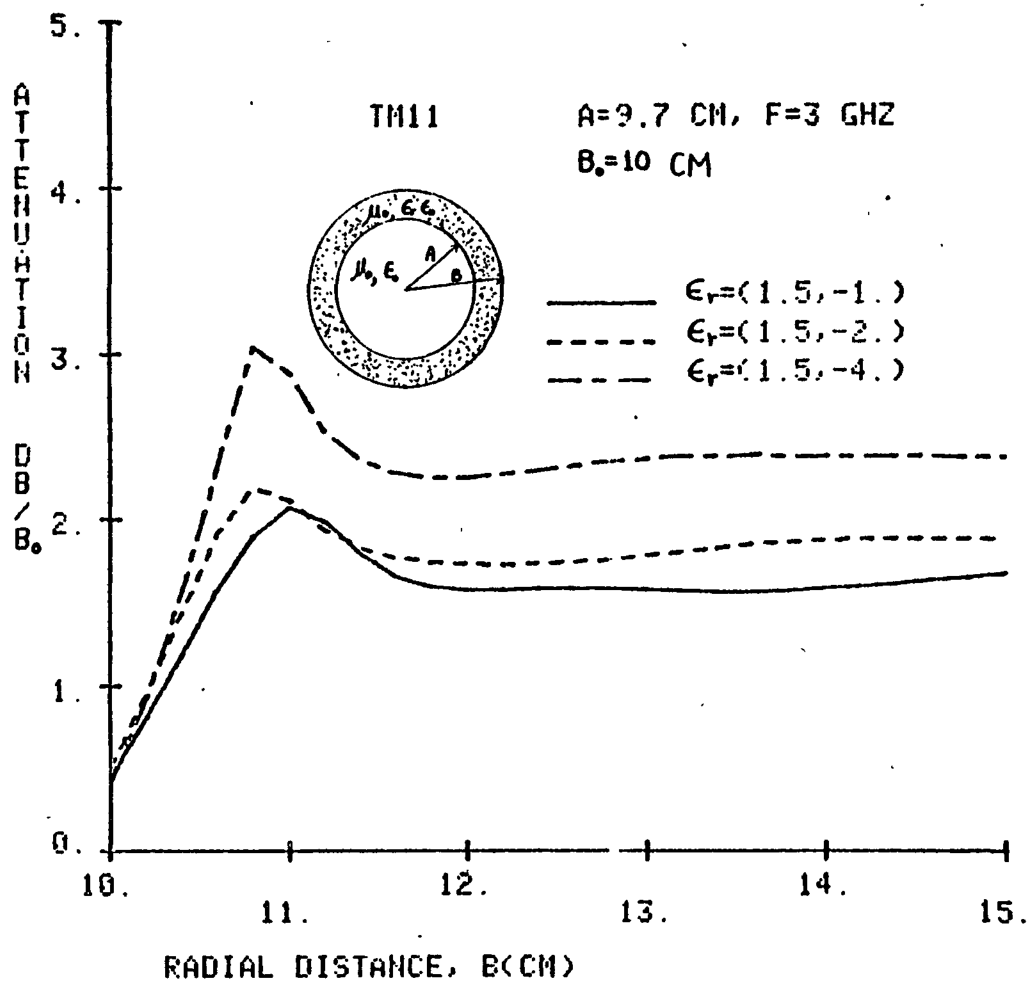

Figure 12. Attenuation constant with variation of B(TM_{11}, $\varepsilon_r^R = 1.5$).

interesting points: 1) There may exist a spatial resonance effect as the layer thickness increases. 2) When we keep the ratio of ε_r^R to ε_r^I constant, the basic dependence of the attenuation constant on the layer thickness remains similar. 3) As ε_r^I increases, the attenuation constant of the TM_{11} mode increases, but the attenuation constant of the TE_{11} mode decreases. In other words, they are mutually exclusive in attaining a large attenuation constant.