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SUPPRESSION OF PROPAGATING TE MODES IN THE FNAL ANTIPROTON

SOURCE STOCHASTIC BEAM COOLING SYSTEM*

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Walter C. Barry

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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Walter C. Barry
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

A method of attenuating the propagation of waveguide modes in the stochastic cooling array beam pipes to be utilized in the accumulator and debuncher rings of the Fermilab antiproton source is described. The attenuation method treated involves lining the vertical walls of the beam pipes with a ferrimagnetic material. The general solution for propagation in a nonhomogeneously loaded waveguide is presented along with numerical results specific to the antiproton source beam cooling system. Also described is a broadband, automated technique for the simultaneous measurement of complex μ and ϵ developed to aid in the characterization of different ferrite materials. Permittivity and permeability data for a typical ferrite is presented along with a discussion of the effects of these parameters on waveguide mode attenuation in the ferrite lined beam pipes.

Introduction

This paper addresses the problem of attenuating the propagation of waveguide modes in the stochastic cooling array beam pipes to be utilized in the accumulator and debuncher rings of the FNAL $\bar{p}$ source.[1] The rectangular geometries of both the 1-2 GHz and 2-4 GHz array beam pipes allow propagation of the TE_{10}, TE_{20}, TE_{30} and TE_{40} modes within the operating band of each pipe. These waveguide modes propagate with a velocity comparable to that of the beam and can induce false signals on the array pickups thereby raising the overall noise level in the system. The method treated here for attenuating these waveguide modes involves lining the vertical walls of the beam pipes with a ferrimagnetic material of complex permittivity and permeability (ϵ and μ). The decision to employ ferrite as the attenuating material was based on its excellent RF attenuating properties, vacuum compatibility, and availability.

The general solution for propagation in a nonhomogeneously loaded waveguide is described along with a broadband, automated technique for simultaneously measuring the complex ϵ and μ of a given ferrite sample. This measurement technique was developed to characterize accurately the electromagnetic properties of the several different ferrites under consideration for the attenuation application. By using the ϵ and μ data measured by this technique in conjunction with the loaded waveguide analysis, the attenuation of TE modes in a beam pipe lined with a given ferrite can be predicted. On this basis a particular ferrite was chosen to line a 2-4 GHz array to be installed in the debuncher ring of the $\bar{p}$ source. Future experiments to determine the effect of this loaded array on noise levels in the debuncher ring are anticipated.

Mode Analysis of Loaded Beam Pipe

Figure 1 depicts the cross section of a waveguide (beam pipe) loaded with two slabs of ferrimagnetic material (regions II and IV) of thickness t_2. The slabs are parallel to the direction of propagation ($\bar{z}$) and at a distance t_1 from each vertical wall. Regions I, III and V are assumed to be free space while regions II and IV have complex permittivities and permeabilities of the form:

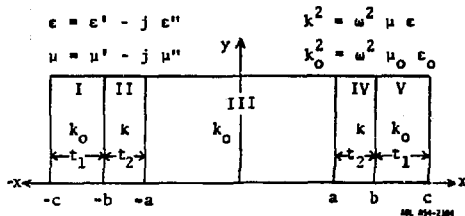$$\epsilon = \epsilon' - j\epsilon'' \qquad \mu = \mu' - j\mu''$$

Fig. 1. Ferrite Loaded Waveguide Geometry

The goal of the analysis is to determine the attenuating effect of the ferrite for the different modes that may be present in the guide. Some insight into the optimum placement of the ferrite for maximum attenuation is also desired. By solving the boundary value problem for the loaded guide, the eigenvalue equations that govern the propagation constants of the odd and even modes in the guide can be obtained. The attenuation of a given mode is then related to the real part of its propagation constant. Because of the length of the analysis, only the pertinent results, the odd and even eigenvalue equations, are presented below. The detailed boundary value analysis may be found in reference [2].

The eigenvalue equations presented are valid for odd and even TE modes with no field variations with the y coordinate. This condition is satisfied for frequencies less than 5 GHz for both the 1-2 GHz and 2-4 GHz arrays whose x,y dimensions are 30 cm, 3 cm and 15 cm, 3 cm respectively. The equations are:

$$\mu_0 \, \ell \tan(pt_1)\Big[\mu_0 \, \ell \tan(\ell t_2) + \mu p \, \tan(pa)\Big]$$
$$= \mu p\Big[\mu_0 \, \ell - \mu p \, \tan(\ell t_2) \, \tan(pa)\Big] \quad \text{Even modes} \quad (1)$$

$$\mu_0 \, \ell \tan(pt_1)\Big[\mu p + \mu_0 \, \ell \tan(pa) \, \tan(\ell t_2)\Big]$$
$$= \mu p\Big[\mu p \, \tan(\ell t_2) - \mu_0 \, \ell \tan(pa)\Big] \quad \text{Odd modes} \quad (2)$$

where:

$$\ell = \sqrt{p^2 + k^2 - k_0^2}$$

$k = \omega\sqrt{\mu\epsilon}$ — Complex wave number in loaded regions

p — Complex eigenvalue for a given mode (analogous to cutoff wave number k_c for an unloaded guide)

t_1, t_2, a — Dimensions as defined in Fig. 1

The attenuation of a mode with eigenvalue p is then given by:

$$a(dB/m) = 8.686 \ Re \ [\gamma(m^{-1})] \qquad (3)$$

where:

$$\gamma = \sqrt{p^2 - k_0^2} \qquad \text{Complex propagation constant}$$

The even and odd modes of (1) and (2) refer to field symmetry about $x = 0$, i.e. $\psi(x) = \psi(-x)$ for even modes and $\psi(x) = -\psi(-x)$ for odd modes. The dominant mode is the even mode with the smallest value of p allowed by (1) and is attenuated the least. Given the physical dimensions t_1, t_2, and a, the attenuation of a mode as a function of frequency may be computed by solving (1) or (2) numerically provided ϵ and μ are known over the band of interest. In order to determine ϵ and μ as a function of frequency for a given sample of ferrite, the measurement technique described below was developed.

Measurement Technique for ϵ and μ

The general technique for determining ϵ and μ involves measuring the complex S parameters for a waveguide or transmission line loaded with the material under test. The technique described here employs a strip transmission line fixture shown in Fig. 2 into which blocks of the material to be measured may be inserted easily. An automated network analyzer system is used to make frequency-swept S-parameter measurements of the loaded stripline fixture. Values for ϵ and μ may then be calculated from the S parameters.
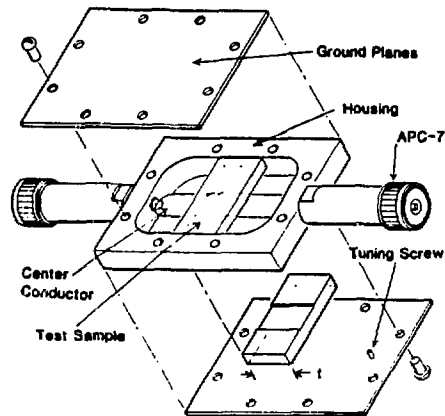

Fig. 2. Stripline Test Fixture for Measuring ϵ and μ

Referring to Fig. 2, an unknown sample material of physical length t is placed in the center of the strip transmission line fixture whose unloaded terminal to terminal electrical length is $2L+t$. For this configuration it can be shown that the complex ϵ_r and μ_r of the sample are related to the S parameters measured at the terminals of the fixture by the following equations:[3]

$$\epsilon_r = \frac{k}{k_0}\left(\frac{1-R}{1+R}\right) \qquad (4)$$

$$\mu_r = \frac{k}{k_0}\left(\frac{1+R}{1-R}\right) \qquad (5)$$

$$k = \frac{1}{t}\cos^{-1}\left(\frac{e^{-j4k_0L} + S_{12}^2 - S_{11}^2}{2e^{-j2k_0L} \ S_{12}}\right) \qquad (6)$$

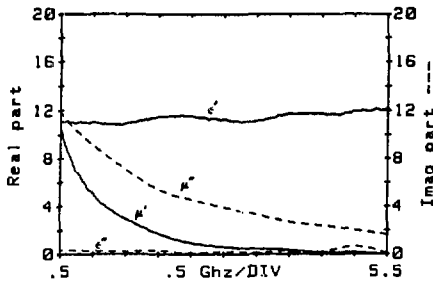$$R = S_{11}\left(e^{-j2k_0L} - S_{12} \ e^{-jkt}\right)^{-1} \qquad (7)$$

It should be noted that when using the above equations the length of the sample should be less than $\lambda_m/2$, in order to avoid dimensional resonances (λ_m is wavelength inside the sample material). For this case the principal branch of the inverse cosine function in (6) may be used.

The accuracy of the measurement technique depends greatly on three major factors; the quality of the stripline to coax match in the fixture, the match of the stripline to the network analyzer (50Ω) and the accuracy of the S-parameter measurements. The first two factors depend on the construction and fine tuning techniques for the fixture, the details of which may be found in reference [3]. The S-parameter measurements were performed with a Hewlett-Packard network analyzer system, the main components of which are an 8410C network analyzer, 8746B S-parameter test set and an 8411A harmonic frequency converter. An HP-9816 computer with appropriate interfacing and peripherals was used for automation, data acquisition, computations and printing/plotting.

For the purpose of assessing the validity of the measurement technique three dielectrics with well known properties - teflon, lucite and polyethylene--were measured over the .5-5.5 GHz band. The measured values of ϵ_r' for the three materials were found to be within better than ± 5% of the generally accepted values of 2.10, 2.26 and 2.60 respectively. As would be expected, $\mu_r' = 1$ was measured in all three cases. For low loss materials such as these ($\epsilon_r'' < .05$ and $\mu_r'' < .05$), the ϵ_r'' and μ_r'' data are inaccurate because of the quality of the matches described above.[3] However, the measurement technique in general was found to be accurate to within better than ± 5% for all cases of ϵ_r and μ_r excluding ϵ_r'' and μ_r'' less than .05.

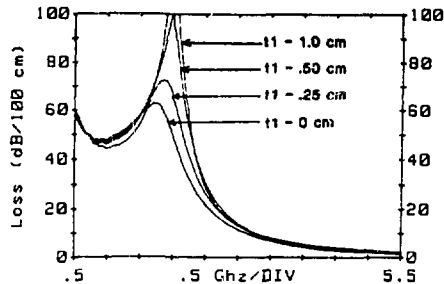### Ferrite Measurements and Attenuation Data for the 2-4 GHz Array

The permittivity and permeability of five different ceramic ferrites were measured over the .5-5.5 GHz band using the above technique. The attenuation afforded by each type of ferrite inside a 2-4 GHz array beam pipe was then evaluated using Eqs. (1), (2) and (3). Figure 3 shows the relative permittivity and permeability of Emerson and Cuming NZ-51 ceramic ferrite tiles, measured as a function of frequency. The data in Fig. 3 are typical of all the ferrite samples that were evaluated. The similarity of the ϵ_r and μ_r data for the different ferrites is attributed to the fact that they are all ceramic compositions of spinal type ferrites with only slightly different mixture formulas. Any variations in ϵ_r and μ_r among the different samples had a negligible effect on attenuation in the 2-4 GHz array. Hence, based on its easy availability, NZ-51 was chosen to line the array.

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Fig. 3. Relative Permittivity and Permeability of NZ-51

References

[1] "The Fermilab Antiproton Source Design Report," Fermi National Accelerator Laboratory, February 1982.

[2] W.C. Barry, "Mode Analysis of Ferrite Loaded Beam Pipe," Lawrence Berkeley Laboratory, LBID-953, August 1984.

[3] W.C. Barry, "A Broadband, Automated, Stripline Technique for the Simultaneous Measurement of Complex Permittivity and Permeability," Lawrence Berkeley Laboratory, February 1985.

The NZ-51 tiles used in the 2-4 GHz array are .5 cm thick, i.e. t_2 = .5 cm in Eqs. (1) and (2). Figure 4 shows the attenuation predicted by Eqs. (1), (2), and (3) of the dominant mode in the array for four different values of t_1. As can be seen, moving the ferrite tiles off the walls (increasing t_1) brings in a resonant-like structure at ~ 2 GHz but has little effect on the attenuation over the rest of the .5-5.5 GHz band. Because of the beam emittance at the location of the 2-4 GHz array in the debuncher, the value of t_1, cannot exceed 2 cm. In view of this requirement, and the insensitivity of the attenuation to variations in t_1 the ferrite was located 1 cm from the walls of the array. This location provides for easy installation and removal of the ferrite. The loaded array is presently scheduled to be installed in the debuncher ring during the last week of April 1985. Tests to evaluate the utility of the ferrite lining should begin sometime in June 1985.

Fig. 4. Attenuation of Dominant Mode in NZ-51 Loaded 2-4 GHz Array.

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