Pbar Note 576

Measurement of Complex Permittivity and Permeability of Microwave Absorber ECCOSORB MF-190

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Introduction

Complex permittivity and permeability of ECCOSORB MF-190 material from Emerson & Cuming company have been measured recently at both room and liquid helium (LHe) temperature to check whether these properties change at LHe temperature.

There are several methods to measure complex permittivity and permeability of materials. A method using reflection measurement has been described by David McGinnis in pbar note #566. With this method, samples are put at the end of a waveguide and terminated with a metal plate. S_{11} parameters from two measurements (two different sample lengths) are used to extract the complex permittivity and permeability.

In the following, another method using S_{21} and S_{11} parameters from one measurement is described. For most materials both methods should work equally well and can be used to check each other. However the second method is more appropriate if: (1) the material has very high permittivity, permeability or attenuation, or (2) the measured properties varies from sample to sample which is not unusual for microwave absorbers according to other lab's report.

Theory of Measurement

The schematic drawing in Figure 1 represents three sections of waveguide (1, 2 and 3) with different complex permittivity and permeability.

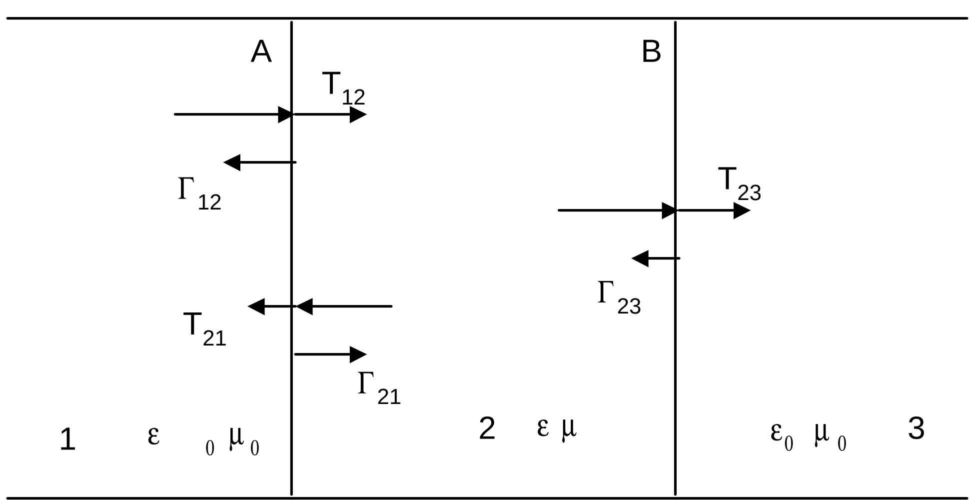

Figure 1. Reflected and Transmitted Signals at Interfaces A and B

When a traveling wave arrives at interface A from section 1, part of it is reflected by a reflected coefficient Γ_{12} and part of it is transmitted by a transmission coefficient T_{12}. The transmitted wave travels through the section 2 (length of *l*) and arrives at interface B. It will be partly reflected by a reflected coefficient Γ_{23} and partly transmitted to section 3 by a transmission coefficient T_{23}. The reflected wave will go back through the section 2 and arrive at interface A. It will be partly reflected by a reflection coefficient Γ_{21} and partly transmitted by a transmission coefficient T_{21}. The reflected wave then goes back to B again, and back to A again and so on ...

The S_{11} measured at interface A and S_{21} measured between interfaces A and B can be deduced as follows.

$$S_{11} = \Gamma_{12} + T_{12}T\Gamma_{23}TT_{21} + T_{12}T\Gamma_{23}T\Gamma_{21}T\Gamma_{23}TT_{21} + \ldots \quad (1)$$

$$S_{21} = T_{12}TT_{23} + T_{12}T\Gamma_{23}T\Gamma_{21}TT_{23} + T_{12}T\Gamma_{23}T\Gamma_{21}TT_{23} + \ldots \quad (2)$$

where $T = e^{-j\beta l}$ (3)
and β is the wave number of a waveguide mode.

Define Γ as:

$$\Gamma = \frac{Z_{absorber} - Z_0}{Z_{absorber} + Z_0} \quad (4)$$

where Z_0 is the characteristic impedance of a waveguide filled with air and $Z_{absorber}$ is the characteristic impedance of the waveguid filled with absorber material.

The other parameters can be expressed as:

$$\Gamma_{12} = \Gamma \quad (5)$$

$$\Gamma_{23} = -\Gamma \quad (6)$$

$$\Gamma_{21} = -\Gamma \quad (7)$$

$$T_{12} = \frac{2Z_{absorber}}{Z_{absorber} + Z_0} = 1 + \Gamma \quad (8)$$

$$T_{21} = T_{23} = \frac{2Z_0}{Z_{absorber} + Z_0} = 1 - \Gamma \quad (9)$$

Insert (5)-(9) into (1):

$$
\begin{aligned}
S_{11} &= \Gamma + (1+\Gamma)T(\text{-}\Gamma)T(1-\Gamma) + (1+\Gamma)T(\text{-}\Gamma)T(\text{-}\Gamma)T(1-\Gamma) + \ldots\ldots \\
&= \Gamma + \frac{(1+\Gamma)T(\text{-}\Gamma)T(1-\Gamma)}{1-(T\Gamma)^2} \\
&= \frac{\Gamma(1-T^2)}{1-(T\Gamma)^2} \qquad (10)
\end{aligned}
$$

Insert (5)-(9) into (2):

$$
\begin{aligned}
S_{21} &= (1+\Gamma)T(1-\Gamma) + (1+\Gamma)T(\text{-}\Gamma)T(\text{-}\Gamma)T(1-\Gamma) + \ldots. \\
&= (1+\Gamma)T(1-\Gamma)\frac{1}{1-(T\Gamma)^2} \\
&= \frac{T(1-\Gamma^2)}{1-(T\Gamma)^2} \qquad (11)
\end{aligned}
$$

Inserting (3) into (10) and (11) and solving these equations, the propagation parameter βl and Γ are found to be:

$$b\,\ell = \arccos\left(\frac{1-S_{11}{}^2+S_{21}{}^2}{2S_{21}}\right) \qquad (12)$$

$$\Gamma = \frac{S_{11}}{1-S_{21}e^{-jb\,\ell}} \qquad (13)$$

For TE_{10} mode of a waveguide, the wave number β and impedance Z are given as:

$$b^2 = k^2 - \left(\frac{p}{a}\right)^2 \qquad (14)$$

$$Z = h\frac{k}{b} \qquad (15)$$

$$h = \sqrt{\frac{m}{e}} = \sqrt{\frac{m_r m_0}{e_r e_0}} \qquad (15)$$

$$k = \sqrt{e_r m_r}\,\frac{w}{c} \qquad (16)$$

$$e = e' + je'' = e_0(e_r' + je_r'') \qquad (17)$$

$$m = m' + jm'' = m_0(m_r' + jm_r'') \qquad (18)$$

where a is the width of the waveguide, ω is frequency and c is the speed of light.

The complex permittivity ε and permeability μ can be calculated from equations (4), and (12)-(18). Note that the S_{11} and S_{21} in the above equations are the S_{11} and S_{21} measured at the interfaces of waveguide 1 and 2 and the interfaces of waveguide 2 and 3. These S parameters can be de-embedded from the S parameters measured at reference planes (left end of waveguide 1 and right end of waveguide 3).

Due to a lot of complex arithmetic operations, there is an $n\pi$ ambiguity when the value of the β is deduced. Several parameters are used to make sure the right n is chosen: the e'' and m'' should be always negative for all frequencies (which means the absorber is absorbing the energy) and e' and m' should be always positive for all frequencies.

Measurement and Results

Samples to be measured are snugly fit into a section of waveguide WR 159 and S parameters were measured using an HP 8510 network analyzer. The section of WR159 was also used in TRL calibration as the LINE standard. A computer program was used to extract permittivity, permeability and loss tangent from S parameters. Several pieces of plexiglass samples were made and measured. The results are compared with published data to check the technique and computer program. These results are shown in Figure 2 and 3. Both methods (reflection and transmission measurement) were used and the results are very close to published data.

To avoid phase ambiguity, MF-190 samples with thickness of 0.06” and 0.1” (less than the half wavelength of the electromagnetic wave in the sample) were used. One sample of MF-190 was measured at liquid helium temperature (5-9 °K). Due to limited time, the TRL calibration was performed at liquid nitrogen temperature (77 °K). The system was cooled down by contacting a liquid nitrogen pipe. In each step of calibration the measurement was taken at three hours after the liquid nitrogen began to flow into the pipe. The calibration is not as good as the calibration at room temperature since it takes three days (three thermal cycles) to complete the calibration and the coax cable to be calibrated is long which can cause inconsistency if it did not reach the same final equilibrium state at 77 °K in each step of calibration. After calibration, the measurement system with a sample of MF-190 (thickness of 0.06 inch) were cooled down to 5-9 °K. Measurement was performed at 8 hours after the system reached 5-9 °K. Shown in Figure 4-7 are permittivity, permeability and loss tangent of MF-190 at room temperature and liquid helium temperature. These results show that data measured at room temperature are close to the data (3-8.6 GHz) obtained from Emerson & Cuming company (permittivity: 28.0-26.0, permeability: 4.5-2.0, dielectric loss tangent: 0.04, magnetic loss tangent: 0.9-1.4.) Although data at LHe temperature are not good due to the calibration problem, they are good enough to show that there is no significant change in dielectric and magnetic properties of MF-190 at LHe temperature which is the main objective of these measurements.

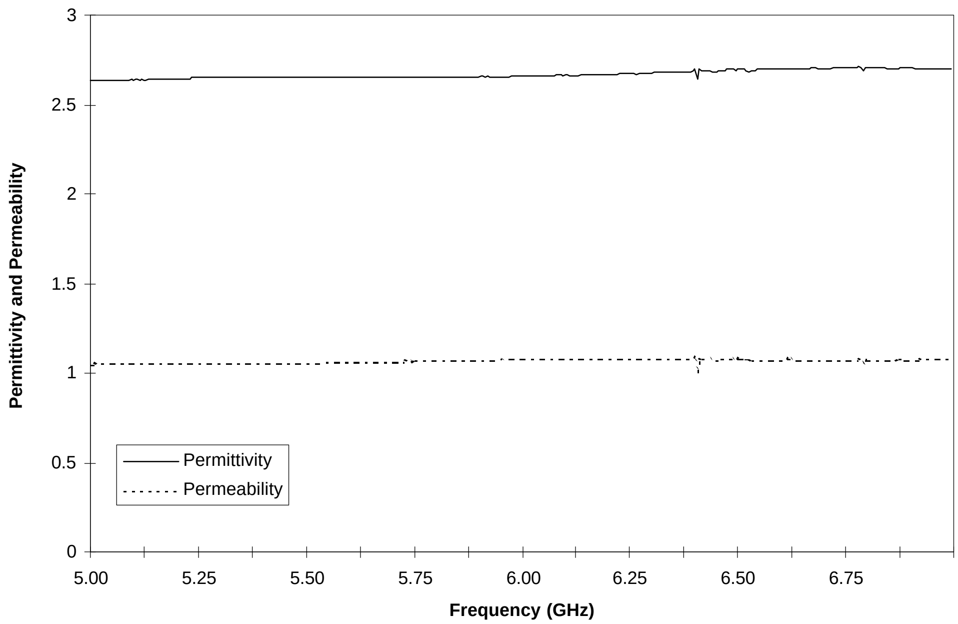

Figure 2. Permittivity and Permeability of Plexiglass

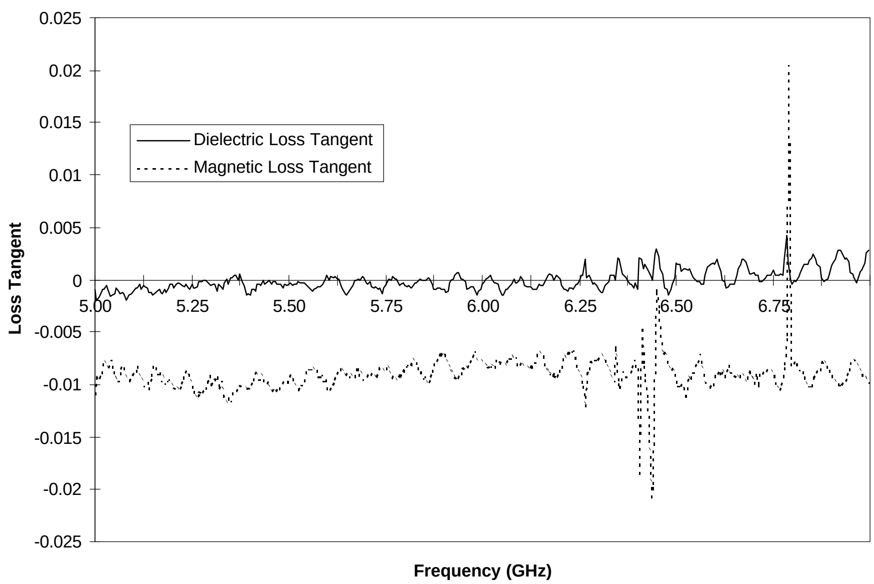

Figure 3. Loss Tangent of Plexiglass

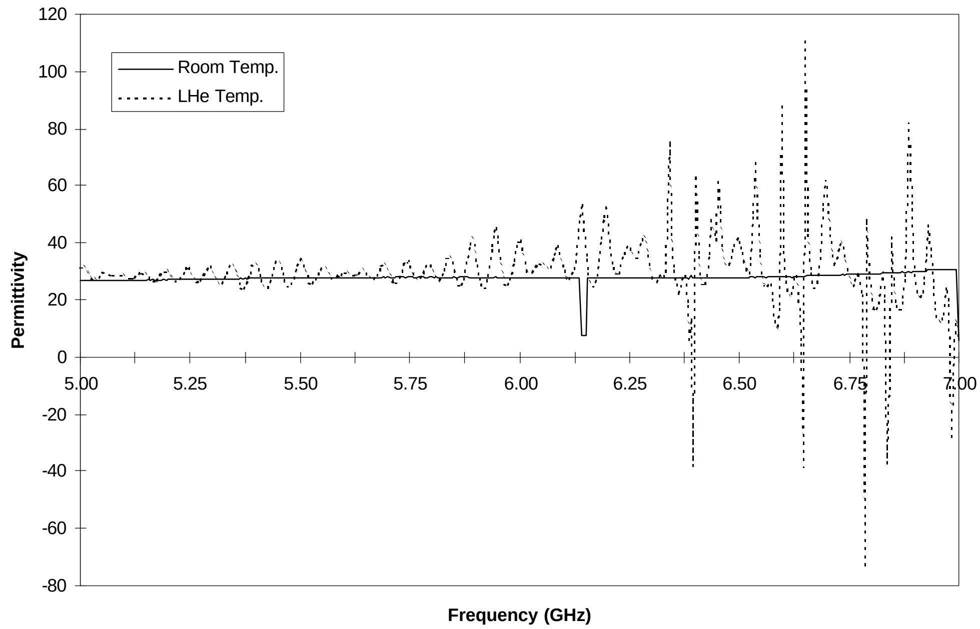

Figure 4. Permittivity of MF-190 Absorber

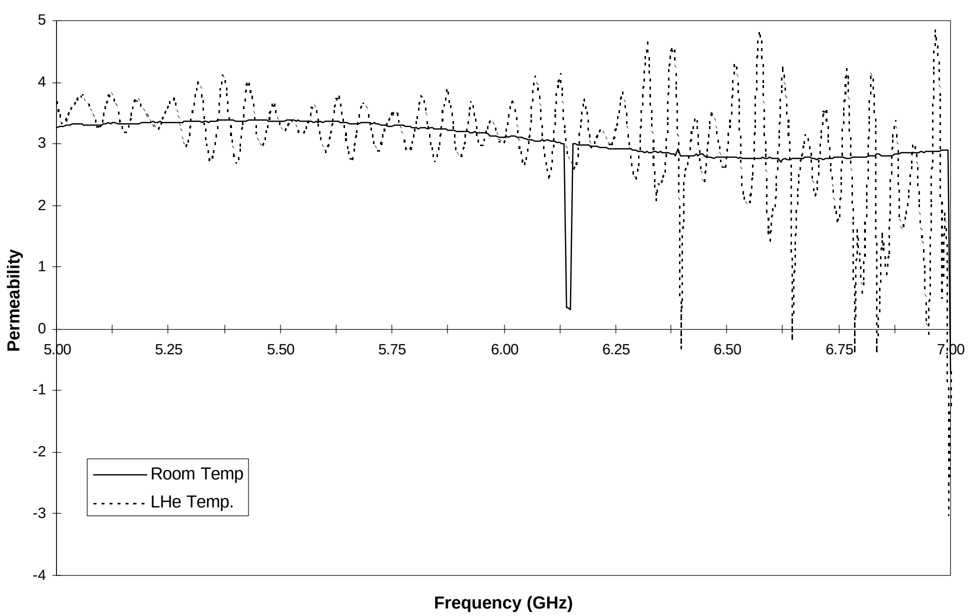

Figure 5. Permeability of MF190 Absorber

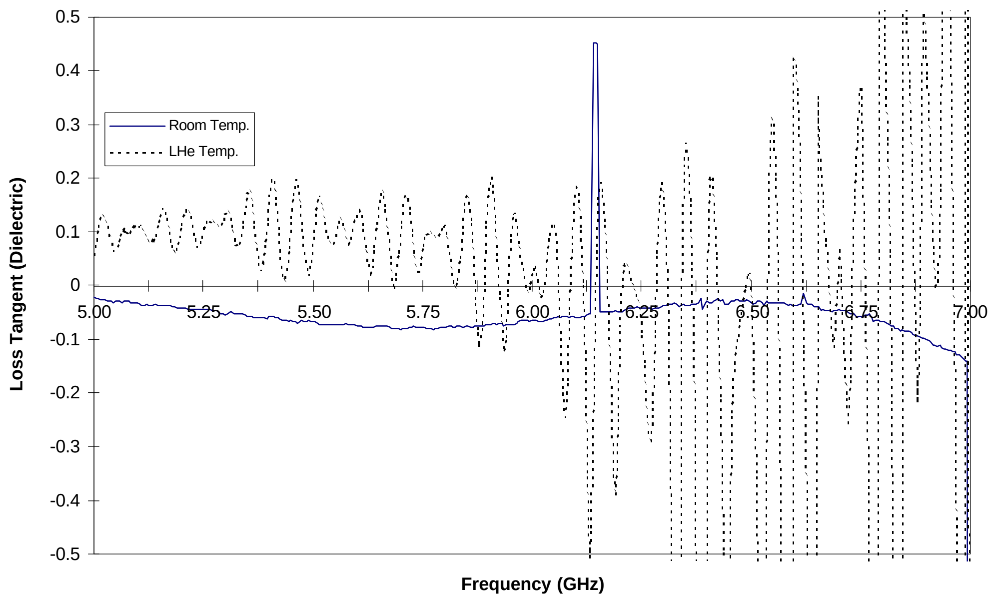

Figure 6. Dielectric Loss Tangent of MF190 Absorber

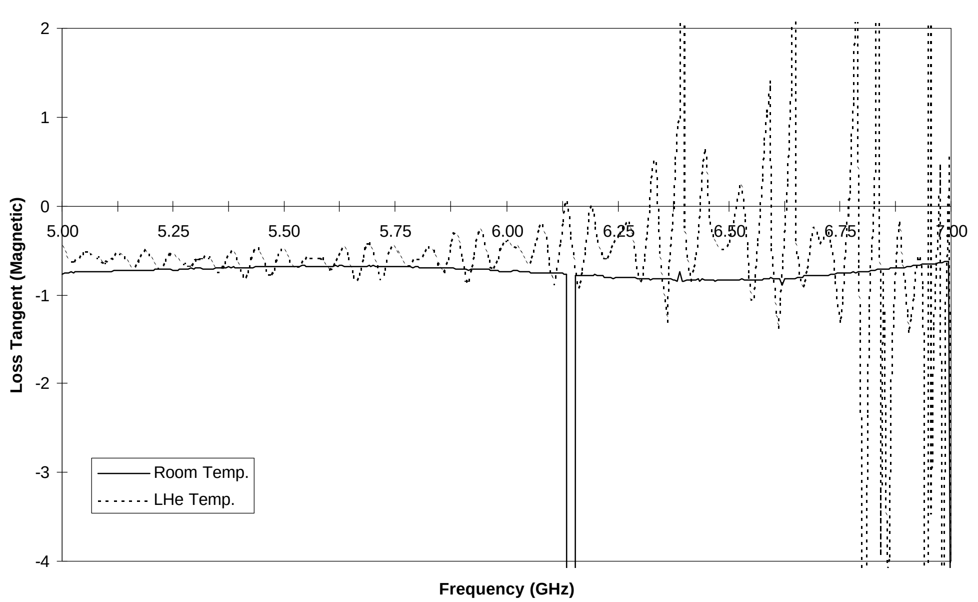

Figure 7. Magnetic Loss Tangent of MF190 Absorber