Fundamental Characteristics of the Microwave Absorber

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Summary

The reflection coefficient and the attenuation factor of the multi-layer absorber are calculated by the application of the transmission line theory, and these values are compared with the measured ones. It is ascertained that both values are in good agreement and that the attenuation factor obtained from the attenuation constant can be of practical use when the reflection coefficient of the absorber is small (VSWR $\lesssim 2$). The incident plane wave which is normal to the absorber is treated. The sample consists of pyrolised polyacrylonitrile fibre blankets.

1. Introduction

Vast space is required for a reduced model experiment, antenna measurement and so on, and occasionally towers are set up on the ground for the purpose of obtaining free space. Then owing to be influenced by wind and rain, an efficient experiment cannot be expected. Therefore, if free space is realized in the room equivalently, a more concise procedure can be selected in these regions. The room equivalent to free space is obtained when the ceiling, the floor and the surroundings of the room are covered over with microwave absorbers, which absorb the microwave without reflection and give attenuation to the wave. This is commonly called a microwave darkroom or an unechoic chamber.

Recently, the microwave darkrooms have been constructed and put into practical use at home and overseas. There are many kinds of absorbers and they may be divided into groups. For example, absorbers consist of a) lossy dielectrics, b) lossy magnetic materials or c) mixture there of; or dividing absorbers into groups by the type for obtaining non-reflection characteristics, there are wedge, multi-layer, shading-off and wavy types.

On the one hand, many kinds of absorbers have been improved by means of cut-and-try method. On the other hand, various theories of multi-layer absorber have been presented, and they are still making efforts for designing conditions for an ideal absorber.[2] The design for the absorber must be based on the analysis of the reflection coefficient and the attenuation factor of various types of high-loss media.

As reflection and attenuation of the stratified high-loss media have not been studied completely, our studies in this paper have two meanings: first, it is ascertained that the reflection coefficient Γ and the attenuation factor S of the multilayer absorber can be calculated by an application of the transmission line theory, where the attenuation factor S is equal to the working attenuation; and second, it becomes obvious that other attenuation factor α_T obtained from the attenuation constant can be used for practice instead of S if the absorber is good-matched to free space. In this paper, the above-meationed parameters of the n-layers absorber are generally given; and at the comparison between theoretical and measured values, the three-layers absorber is adopted.

2. The Reflection Coefficient and the Attenuation Factor

The wave equations in a homogeneous and istropic medium are*

$$(\nabla^2-\gamma^2)E=0, \tag{1}$$

$$(\nabla^2-\gamma^2)H=0, \tag{2}$$

where ∇ is the differential operator defined by

$$\nabla=i\frac{\partial}{\partial x}+j\frac{\partial}{\partial y}+k\frac{\partial}{\partial z},$$

E and H vector electric and magnetic field intensity respectively, γ the intrinsic propagation constant of the medium. γ is defined as

$$\gamma=\sqrt{j\omega\mu(\sigma+j\omega\epsilon)}, \tag{3}$$

where μ is permeability, σ conductivity and ϵ permittivity. Now, let x, y and z be Cartesian coordinates and a uniform plane wave be incident along y axis as shown in Fig. 1(a). P is Poynting vector of the wave. Electric field E polarizes normal to the $y-z$ plane. The general solution of Eq. (1) and (2) becomes

$$E_x=E_R'e^{-\gamma y}+E_R''e^{\gamma y}, \tag{4}$$

$$H_z=\frac{1}{W}(E_R'e^{-\gamma y}-E_y''e^{\gamma y}), \tag{5}$$

where E_x and H_z are the electric and magnetic field intensity, E_R' and E_R'' intensity of the incident and reflected waves at $y=0$ respectively, and W the intrinsic impedance of the medium. W is shown as

$$W=\frac{j\omega\mu}{\gamma}. \tag{6}$$

* See, for example, the refence(1).

The equations (4) and (5) express the electric and magnetic field at distance y, and the solution of the equation concerning with voltage and current at the transmission line is the same type as Eq. (4) and (5). Therefore, it is identified that the relation between electric and magnetic field intensity in the medium is similar to the one between voltage and current at the transmission line; and by use of the transmission line expression, Fig. 1(a) can be rewritten as Fig. 1(b).

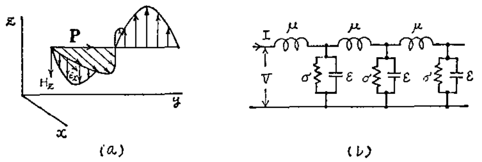

Fig. 1—(a) Schematics of plane-wave propagation in any medium.
(b) Analogous transmission-line for(a).

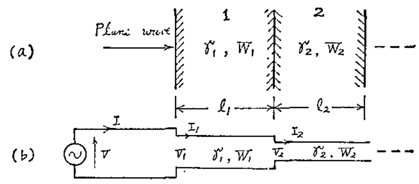

Fig. 2—Analogous plane-wave and transmission-line discontinuities in stratified media.

Now, it is assumed that when the process which a incident plane wave is normal to the medium 1 and which a part of its wave is refrected is replaced by the process which the wave of voltage or current is incident at the transmission line and which a part of its wave is reflected (Fig. 2). Then, the situation can be treated as the transmission line discontinuity. F-matrix expression for one layer becomes

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} \cosh \gamma_1 l_1 & W_1 \sinh \gamma_1 l_1 \\ \frac{1}{W_1} \sinh \gamma_1 l_1 & \cosh \gamma_1 l_1 \end{pmatrix} \begin{pmatrix} V_2 \\ I_2 \end{pmatrix} \tag{7}$$

Generally, F-matrix expression for multi-layer becomes

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \prod_{i=1}^{m} \begin{pmatrix} \cosh \gamma_i l_i & W_i \sinh \gamma_i l_i \\ \frac{1}{W_i} \sinh \gamma_i l_i & \cosh \gamma_i l_i \end{pmatrix} \begin{pmatrix} V_m \\ I_m \end{pmatrix}$$

$$= \prod_{i=1}^{m} \Big(F \Big)_i \begin{pmatrix} V_m \\ I_m \end{pmatrix}, \tag{8}$$

where γ_i is the intrinsic propagation constant, W_i the intrinsic impedance and l_i the thickness of each medium (i=1, 2,..., m). γ_i and W_i are shown as follows:

$$\gamma_i = \alpha_i + j\beta_i,$$

$$W_i = \xi_i + j\eta_i.$$

Moreover, if Eq. (8) becomes

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} V_n \\ I_n \end{pmatrix}, \tag{9}$$

the reflection coefficient of the stratified media is obtained as

$$\Gamma = \frac{Z_0(CZ_m+D)-AZ_m-B}{Z_0(CZ_m+D)+AZ_m+B}, \tag{10}$$

where

$Z_0 = 120\pi$; intrinsic impedance of free space,

$Z_m = V_m/I_m$; intrinsic impedance of the terminator.

When the terminator is a metal plate, ther reflection coefficient becomes

$$\Gamma = \frac{Z_0D-B}{Z_0D+B} \tag{11}$$

The values of the propagation constant γ_i and intrinsic impedance W_i are required for calculating Eq. (10), and these values can be obtained from

$$\left.\begin{aligned} \xi_i &= \sqrt{\frac{\mu_0 \mu_{ri}(\sqrt{1+\tan^2\delta_i}+1)}{2\varepsilon_0\varepsilon_{ri}(1+\tan^2\delta_i)}}, \\ \eta_i &= \sqrt{\frac{\mu_0 \mu_{ri}(\sqrt{1+\tan^2\delta_i}-1)}{2\varepsilon_0\varepsilon_{ri}(1+\tan^2\delta_i)}}, \\ \alpha_i &= \sqrt{\frac{\omega^2\mu_0\mu_{ri}\varepsilon_0\varepsilon_{ri}}{2}(\sqrt{1+\tan^2\delta_i}-1)}, \\ \beta_i &= \sqrt{\frac{\omega^2\mu_0\mu_{ri}\varepsilon_0\varepsilon_{ri}}{2}(\sqrt{1+\tan^2\delta_i}+1)}, \end{aligned}\right\} \tag{12}$$

where $\omega = 2\pi f$. Relative permeability μ_{ri}, relative permittivity ϵ_{ri} and dielectric loss $\tan\delta_i$ in Eq. (12) can be measured by using the standing wave method etc. in the coaxial line or in the waveguide.

It is defined that the attenuation factor S of the stratified media has the ratio (in dB) of the power which is incident to the media to the power which is transmitted through the media. Where, the transmitting source is matched to free space. This attenuation factor is equal to the working attenuation in the transmission line theory. When the stratified media is placed in free space, the attenuation factor S becomes

$$S = 10 \log \left| \frac{1}{2}\left(A + \frac{1}{Z_0}B + Z_0C + D\right)\right|^2 \quad (dB). \tag{13}$$

Other attenuation factor α_T which is obtained from the attenuation constant and the thickness of each layer is defined as

$$\alpha_T = 8.686 \sum_{i=1}^{m} \alpha_i l_i \qquad (dB). \tag{14}$$

Using the above Eq. (10), (13) and (14), the reflection coefficient and the attenuation factor of the multi-layer absorber can be calculated. Although α_T in Eq. (14) is not an exact expression of the attenuation factor, it is used in the reference (4) as a criterion of attenuation. Then, α_T is adopted here for convenience' sake and the comparison between the calculated value and the measured one is tried.

3. Comparison between Theoretical Value and Measured One

3.1 Measured Sample

The sample is shown in Fig. 3. It consists of three layers of pyrolised polyacrylonitrile fibre blankets whose dielectric constants are different from each other. Pyrolised polyacrylonitrile fibre is a thermostable carbon fibre which is made of acryle fibre after heat-treatment of high temperature in inactive gases. The measured values of dielectric constant and other excellent qualities of this fibre are repo'ted at the references (5), (6) and (7). Important qualities of this fibre as the microwave absorber are following.

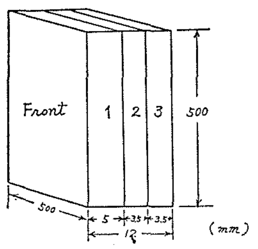

Fig. 3—Structure of the sample.

(a) Various kinds of electric loss (ϵ_r and $\tan\delta$) can easily occur without a loss of their fibrous nature. That is to say, as a vast range of impedance can be used, the design of the microwave absorber becomes easy.

(b) It seems that there is no anomalous dispersion in the frequency band of 1～24 Gc/s. Therefore, this fibre is suitable for material of wideband absorber in this frequency band.

(c) Values of ε_r and $\tan\delta$ of this fibre blanket treated at the temperature of 800°C is very large; therefore, large attenuation can be expected even for the thin sheet of this blanket.

(d) Because directions of fibres in this blanket are a little uniform, the

layer	Permittivity	Frequency (Gc/s)					
	Loss tangent	0. 893	4. 100	6. 000	9. 340	15. 385	24. 000
1st	ε_{r1}	3. 96	1. 27	1. 34	1. 21	1. 30	1. 28
	$\tan\delta_1$	0. 0334	0. 0760	0. 0809	0. 0630	0. 0347	0. 0910
2nd	ε_{r2}	7. 34	1. 36	1. 62	1. 62	1. 60	1. 70
	$\tan\delta_2$	1. 10	0. 487	0. 395	0. 427	0. 477	0. 270
3rd	ε_{r3}	68. 0	17. 7	11. 0	9. 76	8. 61	3. 25
	$\tan\delta_3$	0. 557	1. 95	2. 20	1. 54	1. 25	3. 06

TABLE 1. Measured ε_r and $\tan\delta$ of the sample.

high loss blanket becomes inductive when directions of fibres is in the same one of electric vector. The measurement results of this influence at the frequencies of 9 and 24 Gc/s are reported at the reference (8).

Measured values of dielectric constant are shown in Table 1.

3.2 Measurement Method

As measurement method of the reflection coefficient of the absorber has not been established, a general system of reflecting wave method[9] in free space is adopted here. Measurement frequencies are 4.1, 9.2 and 24 Gc/s. Measurement system at 9.2 Gc/s is shown in Fig. 4 and system at other frequencies are the

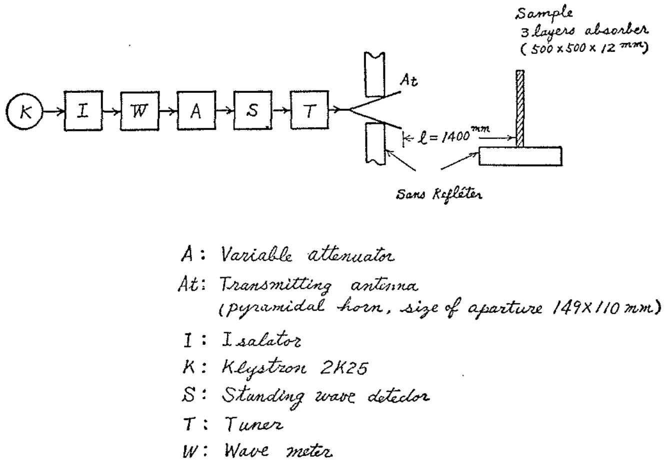

Fig. 4—Measurement system of the reflection coefficient at 9 Gc/s band.

same. The antenna and the sample are set up at the position where incident wave may be considered as plane wave ($l>2D^2/\lambda$, l: the antenna-to-sample spacing, D: largest aperture of the transmitting antenna, λ: wave length in free space) and where the beam half-width of the transmitting antenna is intercepted by the sample. The antenna-to-sample spacing l is 660 mm at 4 Gc/s, 1400 mm at 9 Gc/s and 710 mm at 24 Gc/s band. The pyramidal horn antenna is used at each ferequency band and is sufficiently matched to free space. So as not to be influenced by reflected waves from surroundings, the microwave absorbers (Sans Reflêter) are provided. As shown in Fig. 5, the maximum value ρ_{max} and the minium value ρ_{min} of VSWR (ρ) caused by the sample are obtained in the waveguide when the spacing l is changed. In the same way, $\rho_{s\,max}$ and $\rho_{s\,min}$ are obtained for the metal plate which has the same size as the sample. Next, maximum values $|R_{max}|$ and $|R_{s\,max}|$ and minimum values $|R_{min}|$ and $|R_{smin}|$ of the reflection coefficient in the waveguide are obtained from $|R|=(\rho-1)/(\rho+1)$, and the reflection coefficient $|\Gamma|$ of the sample becomes

$$|\Gamma| = \frac{|R_{max}| \cdot |R_{min}|}{|R_{max}| + |R_{min}|} \bigg/ \frac{|R_{S\,max}| \cdot |R_{min}|}{|R_{S\,max}| + |R_{min}|} \quad . \tag{15}$$

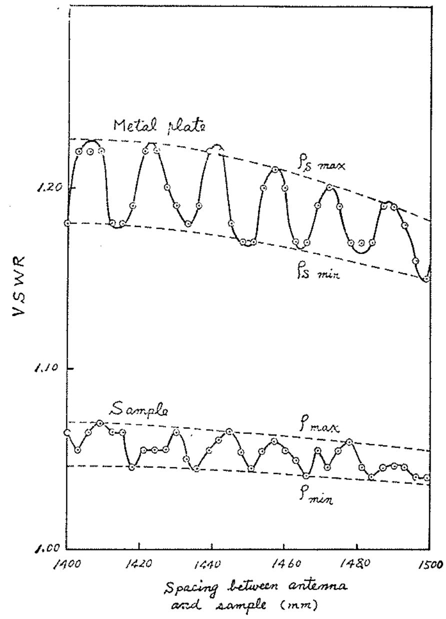

Fig. 5—Measured values of VSWR in rectangular waveguide. (f=9. 2 Gc/s)

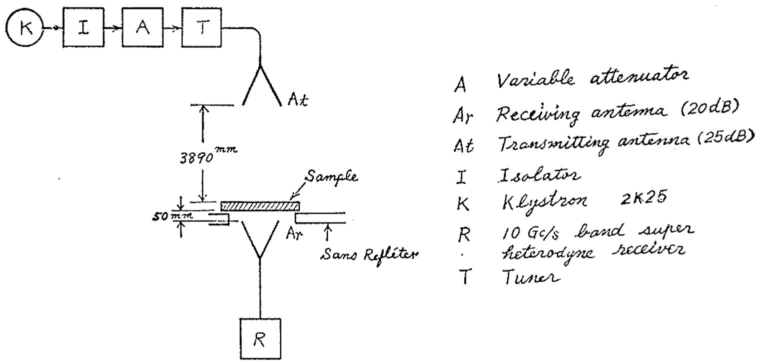

Fig. 6—Measurement system of the attenuation factor at 9 Gc/s band.

Measurement system of the attenuation factor is shown in Fig. 6. The attenuation factor is obtained as the ratio of the receiving power in the absence to the receiving one in the presence of the sample. In this study, the measurement is made at the frequency of 9.2 Gc/s. Pyramidal horns are used as the transmitting and receiving antennas. The transmitting antenna-to-sample spacing is 3890 mm, and the back surface of the sample-to-receiving antenna spacing is 50 mm.

3.3 Discussion

By using expression of VSWR, the calculated value, and the measured one, of the reflection coefficient of the sample are shown in Fig. 7. Obviously the

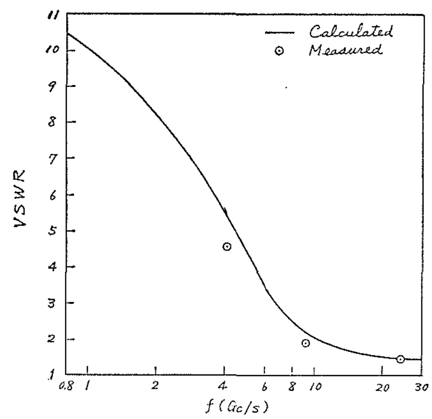

Fig. 7—VSWR of the sample vs. frequency.

result shows that both are in good agreement at each frequency band. It seems to be caused by the error included in the measurement method that small values compared with calculated ones are obtained. As it is reported that the electromagnetic horn antenna is suitable for reflecting wave method, pyramidal horn antenna is used at each frequency band.[9]

In case of this system, the dealing of multi-reflection between the antenna and the sample in the process of introducing the measurement equation is in doubt as discussed in the reference (3). It has been identified experimentally that the measured values of the reflection coefficient have a tendency to become smaller with the antenna-to-sample spacing.[3]

Calculated value and measured one of the above-mentioned two attenuation factors of the sample are shown in Fig. 8. The calculated value and measured one of S are in good agreement. It is obvious from Fig. 7 and Fig. 8 that the calculated value of α_T is smaller than that of S when the absorber is miss-matched to free space and that the calculated value of α_T becomes nearly equal to that of S when the reflection coefficient of the absorber is small (VSWR$\lesssim$ 2).

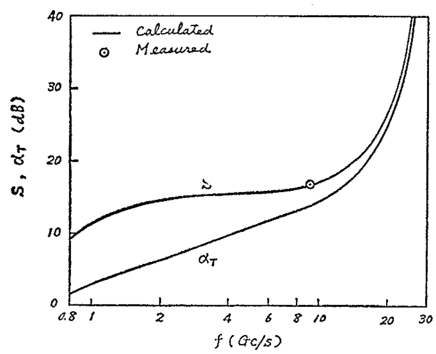

Fig. 8—Attenuation factor of the sample vs. fequency

This results from the absence of the reflection loss at α_T. Therefore, it is ascertained that α_T may be used for the attenuation factor of the good-matched absorber.

4. Conclusion

At the multi-layer absorber, calculated value and measured one of the reflection coefficient and of the attenuation factor are in good agreement as mentioned above. Therefore, it is identified that these calculation methods of Γ and S can be applied for the multi-layer absorber and that α_T can be used for the attenuation factor of the good-matched absorber. The general treatment of theory and meaurement including oblique incidence with both normal and parallel polarizations will be reported some time later.

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マイクロ波電波吸収材の基礎特性

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多層形電波吸収材に良く知られている伝送線路理論を適用し，マイクロ波帯において反射係数と透過減衰量（線路理論における動作減衰量に等しい）を計算し実測値と比較検討した。その結果両者は比較的良く一致すること，又整合特性の良い電波吸収材の透過減衰量は減衰定数から得られる減衰量を用いて実用上差支えないことが判明した。たゞし本論文では電波の垂直入射の場合のみを取扱う。