Theoretical Limitations on Shielding and Reflective Properties of Microwave Absorbers

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Abstract— **In this paper we investigate theoretical limitations of the reflective and absorptive properties of a single-layer passive homogeneous microwave absorber that follows solely from the boundary conditions applied to the flat plane surface which separates the air (vacuum) and absorber half-spaces. Dielectric, magnetic and magneto-dielectric passive absorbers have been considered. Following this, examples of multi-layer absorber designs, which help to overcome the above limitations have been investigated and compared with a single-layer case.**

I. INTRODUCTION

A growing number of commercial and military applications that require microwave absorbers with low reflectivity accompanied by high EM shielding effectiveness [1] have stimulated the development of novel microwave absorbing materials [2] whose dielectric and potentially magnetic properties may be optimized for particular applications.

In this paper we investigate optimal combinations of complex permittivity and permeability of passive microwave absorbers which yield concurrently the lowest reflectivity and highest EM shielding effectiveness.

We begin with the single-layer absorber case using the well known expressions for the EM wave reflection coefficient and attenuation constant on the plane boundary surface between two homogeneous half-spaces [3]. Next, we optimize multi-layer absorber structures and compare their performance with that of the single-layer absorber.

II. SINGLE-LAYER ABSORBER CASE

Let us consider a plane wave that propagates from the homogeneous half-space 1 (vacuum) to the homogeneous half-space 2 (absorber) at an incidence angle θ_1 with the refraction angle θ_2 related to each other by Snell's law. The relative refractive index n_{21} and the relative wave propagation impedance z_{21} of medium 2 in respect to medium 1 are defined through the complex relative permittivity ε and permeability μ of the absorber material:

$$
\begin{aligned}
n_{21} &= \sqrt{\mu\varepsilon} = \sqrt{\mu_r(1-j\tan\delta_\mu)\,\varepsilon_r(1-j\tan\delta_\varepsilon)} \\
z_{21} &= \sqrt{\mu/\varepsilon} = \sqrt{\mu_r(1-j\tan\delta_\mu)/\varepsilon_r(1-j\tan\delta_\varepsilon)}
\end{aligned} \tag{1}
$$

Application of the boundary conditions leads to the following expressions for TE and TM reflection coefficients and the normal-to-boundary-surface component of complex wave propagation vector within the absorber [3]:

$$
\begin{aligned}
k_{2n} &= k_1\sqrt{n_{21}^2 - \sin^2\theta_1} = k_1(\beta - j\alpha) \\
R_{TE} &= \frac{\cos\theta_2 - z_{21}\cos\theta_1}{z_{21}\cos\theta_1 + \cos\theta_2} \\
R_{TM} &= \frac{\cos\theta_1 - z_{21}\cos\theta_2}{z_{21}\cos\theta_2 + \cos\theta_1}
\end{aligned} \tag{2}
$$

where k_1 is the wave number in vacuum, k_{2n} is the normal-to-boundary-surface component of the complex wave propagation vector within the absorber, and α is the absorber relative attenuation constant that causes an attenuation within the absorber by 54.575α dB per wavelength in vacuum.

Thus, according to (2), the reflectivity of the single-layer absorber depends both on z_{21} and n_{21} values, while the attenuation within the absorber depends only on n_{21}.

It should be noted that since (1) - (2) have been written in relative material parameters terms, all considerations in this paper are valid for any two homogeneous media.

A. Magneto-Dielectric Absorber

This is the most advanced type of absorbing material because, according to (1), it is possible to achieve the desirable values of n_{21} and z_{21} simultaneously by varying its ε and μ material parameters.

According to (1) - (2), to obtain the minimum reflection while producing maximum attenuation, the value z_{21} must equal 1 (causing no reflection at normal incidence), while the value of n_{21} should have the largest possible imaginary part. Hence, the complex permittivity and permeability of the optimal magneto-dielectric absorber must be equal to each other and, under this condition, k_{2n} becomes:

$$
k_{2n}(\varepsilon = \mu) = k_1(\beta - j\alpha) = k_1\sqrt{\varepsilon^2 - \sin^2\theta_1} \tag{3}
$$

As it follows from (3), the value of α/ε_r approaches the value of the loss tangent when the absolute value of ε and μ

becomes significantly greater than *sin* θ_1. Moreover, the plots in Figure 1 show that the value of α/ε_r is not too far from the value of the loss tangent for any values of ε and *sin* θ_1.

Solid Red - $\varepsilon_r = 1$, $\theta_1 = 0°$
Long-Dashed Dark Blue - $\varepsilon_r = 1$, $\theta_1 = 85°$
Short-Dashed Green - $\varepsilon_r = 1.4$, $\theta_1 = 85°$
Dot-Dashed Light Blue - $\varepsilon_r = 2$, $\theta_1 = 85°$

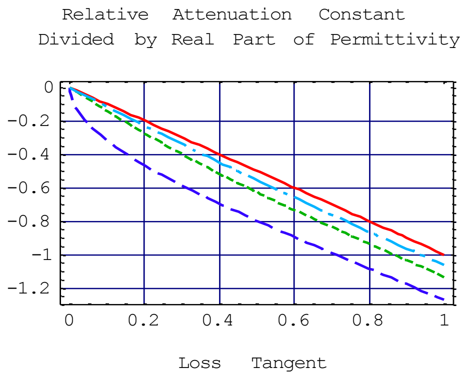


Fig. 1 Absorber attenuation at different incident angles and absorber permittivity for optimal magneto-dielectric absorber.

Solid Red - $\theta_1 = 30°$
Long-Dashed Dark Blue - $\theta_1 = 45°$
Short-Dashed Green - $\theta_1 = 60°$
Dot-Dashed Light Blue - $\theta_1 = 75°$
Double Dot-Dashed Yellow - $\theta_1 = 85°$

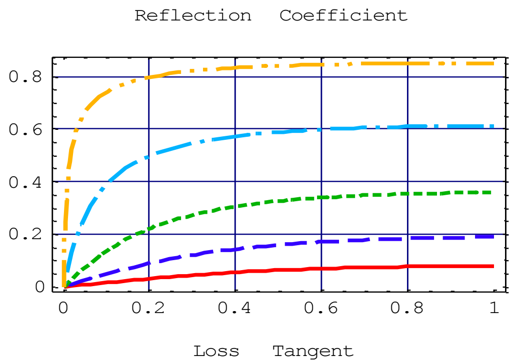


Fig. 2 Absolute value of reflection coefficient at different incident angles and absorber permittivity $\varepsilon_r = 1$ for optimal magneto-dielectric absorber.

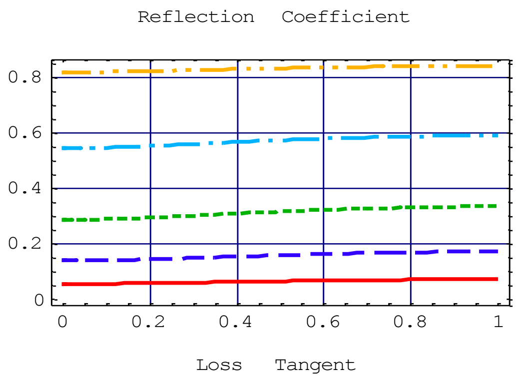


Fig. 3 Absolute value of reflection coefficient at different incident angles and absorber permittivity $\varepsilon_r = 2$ for optimal magneto-dielectric absorber.

It can be concluded that the relative attenuation constant α of the optimal ($\varepsilon = \mu$) magneto-dielectric absorber asymptotically is proportional to the imaginary part of its permittivity or permeability.

As it follows from (2) and is illustrated by the plots in Figures 2 and 3, the absolute values of TE and TM reflection coefficients of the optimal magneto-dielectric absorber are equal to each other and approach the following limit when the absolute value of ε and μ becomes significantly greater than 1:

$$R = (1-\cos\theta_1)/(1+\cos\theta_1) \qquad (4)$$

Thus, unless the loss tangent of the optimal magneto-dielectric absorber is close to zero and/or the real part of permittivity (permeability) is close to 1, its reflectivity does not noticeably depend on the loss tangent. Under these conditions, the EM shielding properties of the optimal magneto-dielectric absorber can be further enhanced by increasing the absorber loss tangent without compromising its reflectivity.

B. *Magnetic or Dielectric Absorber*

This kind of absorbing material has less potential than the optimal magneto-dielectric one, because it is not possible to concurrently achieve the desirable values n_{21} and z_{21} by varying just one absorber material parameter (ε or μ). This means, for instance, that the reflectivity of such absorbers can not be equal to zero even at normal incidence.

The expressions (1) – (2) are transposable with respect to the following substitutions: $\varepsilon \leftrightarrow \mu$, $n_{21} \leftrightarrow n_{21}$, $z_{21} \leftrightarrow 1/z_{21}$, $R_{TE} \leftrightarrow -R_{TM}$. Thus, only the dielectric absorber case has been investigated further in this paragraph.

Solid Red - $\varepsilon_r = 1$, $\theta_1 = 0°$
Long-Dashed Dark Blue - $\varepsilon_r = 1$, $\theta_1 = 85°$
Short-Dashed Green - $\varepsilon_r = 1.4$, $\theta_1 = 85°$
Dot-Dashed Light Blue - $\varepsilon_r = 2$, $\theta_1 = 85°$

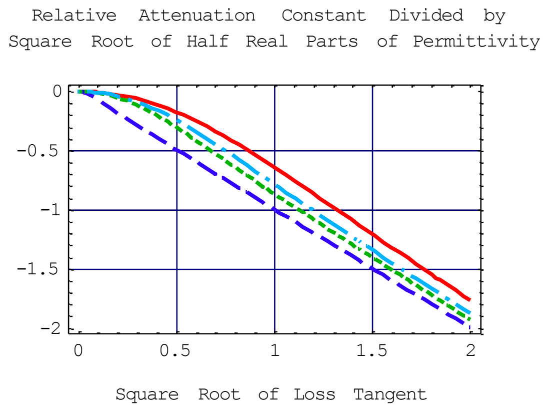
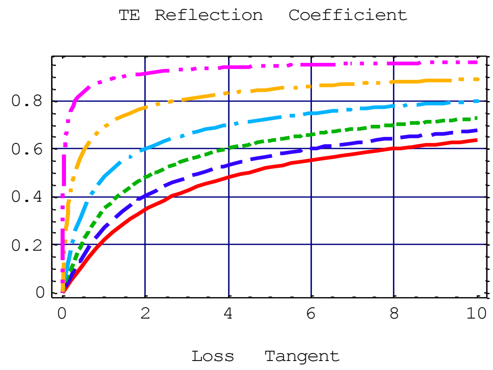


Fig. 4 Absorber attenuation at different incident angles and absorber permittivity for dielectric only absorber.

As may be seen from (1) – (2), the value of $\alpha / (0.5\varepsilon_r)^{1/2}$ approaches the square root of the loss tangent for the dielectric (magnetic) absorber when the absolute value of ε becomes significantly greater than *sin* θ_1. The plots in Figure 4 show that the value of $\alpha / (0.5\varepsilon_r)^{1/2}$ is not too far from the value of $(\tan\delta)^{1/2}$ for any values of ε and $\sin\theta_1$.

Solid Red - $\theta_1 = 0°$
Long-Dashed Dark Blue - $\theta_1 = 30°$
Short-Dashed Green - $\theta_1 = 45°$
Dot-Dashed Light Blue - $\theta_1 = 60°$
Double Dot-Dashed Yellow - $\theta_1 = 75°$
Triple Dot-Dashed Purple - $\theta_1 = 85°$



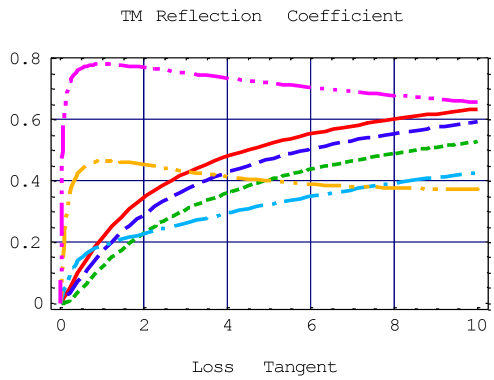


Fig. 5 Absolute value of TE and TM reflection coefficients at different incident angles and absorber permittivity $\varepsilon_r = 1$ for dielectric absorber.

So, the relative attenuation constant α of the dielectric (magnetic) absorber asymptotically is being proportional to the square root of its permittivity (permeability).

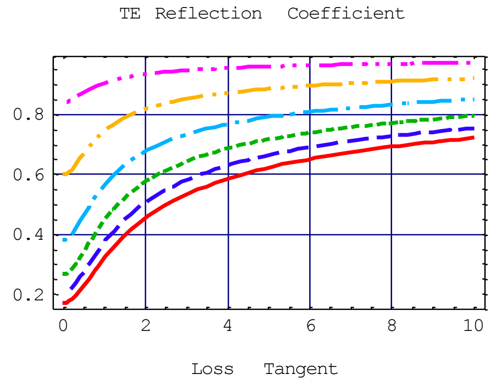
Unlike the optimal magneto-dielectric absorber case, the absolute value of TE and TM reflection coefficient of the dielectric (magnetic) absorber slowly (see (1), (2) and plots in Figures 5 and 6) approach 1 with the increase of either the absorber permittivity or the loss tangent.

It can be concluded that, except for high incident angles, the reflective and shielding properties of the dielectric (magnetic) absorber have the opposite behaviour – the improvement in one can only be achieved at the expense of the other.

III. Examples of Multi-Layer Absorber Optimization

In this section the examples of two and three-layer absorber designs that help overcome the shortcomings of the single-layer design limits are considered. Specifically, the hypothetical optimal magneto-dielectric, dielectric (magnetic), and the actual nanocomposite [2] absorber designs that have minimum reflection at the 8-16 GHz frequency band within the 0° - 30° range of the incidence angles, while having greater than -22 dB shielding effectiveness were found by using the GA optimization.

Solid Red - $\theta_1 = 0°$
Long-Dashed Dark Blue - $\theta_1 = 30°$
Short-Dashed Green - $\theta_1 = 45°$
Dot-Dashed Light Blue - $\theta_1 = 60°$
Double Dot-Dashed Yellow - $\theta_1 = 75°$
Triple Dot-Dashed Purple - $\theta_1 = 85°$



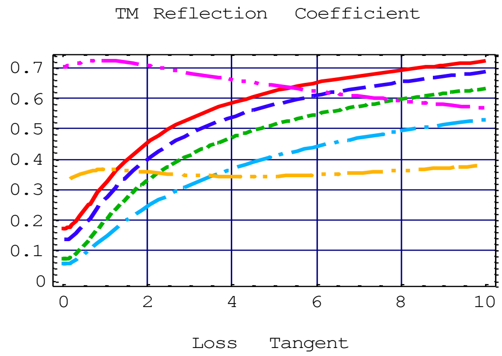


Fig. 6 Absolute value of TE and TM reflection coefficients at different incident angles and absorber permittivity $\varepsilon_r = 2$ for dielectric absorber.

A. *Description of Absorber Materials*

A description of the considered absorber materials is shown in Table I. To make a meaningful comparison with the nanocomposite absorber design [2], the total absorber layer thickness of 1.18 inches was used for all cases.

TABLE I
DESCRIPTION OF COMPARED ABSORBER MATERIALS

Absorber ID	Absorber Description
1	Optimal magneto-dielectric (see section II *A*)
2	Dielectric (magnetic) only (see section II *B*)
3	Nanocomposite dielectric [2] (optimal design)
4	Nanocomposite dielectric [2] (design from [2])

B. *One, Two and Three-Layer Absorber Designs*

The results of one, two and three-layer absorber design optimization are shown in Tables II - IV. Data for the absorber #4 in Tables II and IV was taken from [2].

By comparing the different kinds of absorber materials, it can be concluded that the optimal magneto-dielectric absorber yields much better performance than the dielectric (magnetic) only one. On the other hand, the performance of the optimal dielectric absorber is not too far from the performance of the actual nanocomposite dielectric [2] with the optimal concentration of nanotubes, and is noticeably better than the performance of its original design [2], where those concentrations were not fully optimized.

TABLE III
MAXIMUM REFLECTION IN BAND OF SINGLE LAYER ABSORBER

Absorber ID	Thickness, inch	Permittivity (Permeability)	Maximum Reflection, dB
1	1.18	1.355 – j0.504	-25.41
2	1.18	1.136 – j1.203	-10.66
3	1.18	2.057 – j1.008	-9.64
4	1.18	1.85 – j0.30	-6.5

TABLE IIIII
MAXIMUM REFLECTION IN BAND OF TWO LAYER ABSORBER

Absorber ID	Thickness, inch	Permittivity (Permeability)	Maximum Reflection, dB
1	0.989 0.189	1.277 – j0.587 1.227 – j0.077	-32.55
2	0.999 0.174	1.000 – j1.331 1.417 – j0.417	-18.27
3	0.950 0.227	2.224- j1.240 1.486 – j0.295	-16.41

TABLE IVV
MAXIMUM REFLECTION IN BAND OF THREE LAYER ABSORBER

Absorber ID	Thickness, inch	Permittivity (Permeability)	Maximum Reflection, dB
1	0.781 0.286 0.146	1.23 – j0.698 1.187 – j0.261 1.154 – j0	-44.30
2	0.778 0.234 0.123	1.136 – j1.699 1.350 – j0.737 1.429 – j0.063	-29.14
3	0.746 0.215 0.202	2.49 – j1.556 1.726 – j0.595 1.324 – j0.093	-25.61
4	0.276 0.433 0.472	3.65 – j1.20 2.45 – j0.60 1.85 – j0.30	-9.0

Comparing one, two and three-layer absorber designs it can be concluded that the use of two absorber layers instead of one decreases the reflection coefficient by about 8 dB for all types of the absorber materials and the use of three-layer absorber design instead of two gives the additional decrease of the reflection coefficient by another 8-12 dB.

Comparing the three-layer optimal design using the actual nanocomposite absorber [2] and the one-layer design using the hypothetical optimal dielectric (magnetic), or even magneto-dielectric material, it can be concluded that the application of the multi-layer absorber can overcome the theoretical limitations of the reflective and absorptive properties of a single-layer absorber.

IV. CONCLUSIONS

The investigation of the theoretical limitations of the reflective and absorptive properties of a single-layer passive homogeneous microwave absorber, as well as comparison of those limitations with the multi-layer absorber design cases, lead us to the following observations:

a) The optimal magneto-dielectrics ($\varepsilon = \mu$) are the most advantageous absorber materials in terms of having minimum possible reflection at given thickness and shielding effectiveness of the absorber layer. Conversely, for a given reflectivity, the EM shielding properties of those absorbers can be unlimitedly increased by maximizing the absorber loss tangent, unless the reflection requirements are extremely low or the incidence angle is too close to 90º.

b) The properties of a dielectric or magnetic only absorber materials are reciprocal (see section II *B*). That enables us to consider them as a one type of absorber materials from the standpoint of its EM performance. Its performance is significantly worse than that of the optimal magneto-dielectric material. Also, unlike the latter, its reflective and shielding properties, as a rule, have an opposite behaviour.

c) Application of the multi-layer absorber design enables us to overcome the limitations of the single-layer one. For instance, we can achieve better results by using three layers of actual nanocomposite absorber [2], rather than using just one layer of the best possible magneto-dielectric material.

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