# Application Notes

## Cavity-Resonance Dampening

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Today, many microwave circuit designers are noticing that their circuits do not perform quite as well as predicted when they enclose their circuit boards within a package. Cavity resonances are generated inside the package that can change the impedances necessary for proper operation of some circuit elements. With frequencies of operation increasing, this is becoming an increasingly prevalent issue in circuit design.

### What is a Cavity Resonance?

Solutions to the field equations inside an enclosed space (cavity) reveal the possible existence of standing wave modes. These modes can exist in an empty rectangular cavity if the largest cavity dimension is greater than or equal to one half a free space wavelength. Below this cutoff frequency, the cavity resonance cannot exist.

Figure 1 shows a rectangular cavity with dimensions $a$, $b$, $c$, with $a < b < c$, that is completely filled with a homogeneous material.

Cavity resonances can occur at the following frequencies:

$$(f)_{mnp} = \frac{1}{2\sqrt{\varepsilon\mu}}\sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{c}\right)^2}, \qquad (1)$$

where $\varepsilon$ is the material permittivity, $\mu$ is the material permeability, and $m$, $n$, and $p$ are integers [1].

In this configuration, the $TE_{011}$ mode is the dominant mode, because it occurs at the lowest frequency at which a cavity resonance can exist. From (1), it can be seen that the frequency at which this dominant resonance mode can exist (the cutoff frequency) is inversely proportional to the square root of the product of material parameter magnitudes $\varepsilon$ and $\mu$. If the circuit's frequency of operation is below the cutoff frequency of the cavity, there will not be a problem with cavity resonances, as their existence will be precluded by (1).

### What's Wrong with Cavity Resonances?

Cavity resonance becomes an issue when a circuit is designed, built, and works well but must be protected and/or shielded with a circuit-board cover. For shielding purposes, the covers are made of or lined with metal. This creates a cavity above the circuit board where resonances can exist. With operating frequencies going higher into the microwave- and millimeter-wave bands, cavity-resonance effects have become a major problem.

Solutions to the field equations for the $TE_{011}$ mode in a rectangular cavity surrounded by a perfect conductor are as follows [1, p. 75]:

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$$E_x = E_0 \sin\left(\frac{\pi y}{b}\right) \sin\left(\frac{\pi z}{c}\right) \tag{2}$$

$$H_y = \frac{jbE_0}{\eta\sqrt{b^2 + c^2}} \sin\left(\frac{\pi y}{b}\right) \cos\left(\frac{\pi z}{c}\right) \tag{3}$$

$$H_z = -\frac{jcE_0}{\eta\sqrt{b^2 + c^2}} \cos\left(\frac{\pi y}{b}\right) \sin\left(\frac{\pi z}{c}\right) \tag{4}$$

$$\eta = \sqrt{\frac{\mu}{\varepsilon}} \tag{5}$$

In (2)–(4), the $x$, $y$, and $z$ axes have been oriented along the shortest, next-to-shortest, and longest dimensions of the cavity, respectively, and $E_0$ is defined as the normalized electric field. From the $j$ in (2) and (3), we note that the standing wave has the characteristic that the $E$ and $H$ fields are 90° out of phase with each other. The ratio of the instantaneous electric and magnetic field intensities throughout the cavity will fluctuate wildly as a function of position, causing unknown (usually undesirable) effects on circuitry, including the introduction of instability to active devices. The $H$ field also is at its maximum at the wall of the cavity, which may result in reduced shielding effectiveness at the resonant frequencies. Often, what is perceived as a shielding issue requiring attention to shielding materials is actually a cavity-resonance issue.

## Fixing Cavity-Resonance Problems

The goal of any fix to a cavity-resonance issue is to reduce the level of the voltage standing wave ratio (VSWR) at the key points. These points could be the input or output of an active device, of a microstrip filter, or of even a simple through line to another circuit element. If the size of the cavity can be reduced, the cutoff frequency will perhaps be forced too high to cause problems in the circuit. Often, however, it is not feasible to increase the cavity size without adversely affecting circuit performance.

Relocating a particular circuit element to a different position in the cavity can often fix the problem. Intelligent positioning of posts or other objects to disrupt the standing wave can also be helpful, but both of these methods can involve an investment in engineering design time and possible manufacturing delays.

Using microwave-absorbent material in the cavity has proven to be very effective at dampening the resonance. Absorbers (particularly of the magnetic variety) have extremely high values for permittivity and permeability, as well as high loss values. Recall the basic definitions of permittivity and permeability as the ability to store electric and magnetic energy, respectively. When introduced into the cavity, solutions to the field equations show that the energy resides primarily in the high-$\varepsilon$/high-$\mu$ material. This reduces the energy available in the empty area of the cavity containing the circuit, which reduces the impedance variation and its effect on the circuit.

Figure 2 is an example of an electromagnetic simulation of the standing wave fields (specify $E$, $H$, or both) inside an empty cavity. Shown is the $TE_{032}$ mode in a 3 × 5 × 0.8-in cavity with resonant frequency 4.57 GHz. The three drawings represent standing-wave field strength (in volts) at three different phase points (0°, 45°, 112.5°). Note how the energy is evenly distributed throughout the cavity.

Figure 3 shows electromagnetic simulation of the same cavity shown in Figure 2, but including a thin magnetically lossy absorber material. Note how the electromagnetic energy resides almost entirely within the absorber material. Use of the absorber dramatically decreases the level of the VSWR in the empty portion of the cavity.

Electromagnetic modeling of the field solutions inside a partially filled cavity is straightforward, if somewhat complex and computationally difficult. Figures 2 and 3 took nearly a day to generate. Newer versions of popular circuit modeling software will incorporate libraries of absorber parameters to help predict the effect of the introduction of absorber material.

## What Type of Material is Best Suited for Cavity-Resonance Dampening Applications?

In choosing an absorber material, it is important to recognize the difference between absorbers intended for use in free space and absorbers intended for use in cavities. A free-space absorber will generally be characterized as resonant at a particular frequency or narrow range of frequencies. This is due to the fact that the material absorbs best in free space when it is a quarter wavelength thick, and this, of course, only occurs at one frequency. For example, ECCOSORB SF-10 is a magnetically loaded free space absorber resonant at 10 GHz. The physical thickness is 0.056 in. It will reduce reflections off a metal surface by 20 dB.

There is nothing inherent in the material that resonates at that frequency. It is only due to the material thickness that the absorber resonates at one frequency in free space. Most microwave-absorbent materials inherently absorb energy over a wide range of frequencies in the microwave band. In the microwave band, the loss tangent of a typical material will drop with increasing frequency. However, since the wavelength is also shortened, the total attenuation loss per centimeter of travel increases. As noted previously, high values for permittivity and permeability, as well as high loss values, are desirable. Also, the fact that tangential $E$ field of a standing wave is zero on the walls where the absorber is likely to be located, whereas the $H$ field is a maximum there, makes a magnetic absorber more effective, albeit at a higher cost.

The important factors to consider when choosing a cavity-resonance absorber include:

- absorber material
- thickness
- absorber placement in cavity
- ease of application
- cost.

Each of these is discussed separately in this article.

## Absorber Material

As noted previously, absorbers for cavity-resonance applications are inherently broadband in that they exhibit high magnetic and/or dielectric loss over a broad range of frequencies. Some materials will work better in the lower microwave range while others will work better at the higher microwave and millimeter-wave range. A perusal of a manufacturer's catalog would seem to imply that certain materials resonate at particular frequencies and that these materials are rather narrowband. This does not apply to a cavity-resonance situation. In an enclosed space, this is not a factor, and the proper metric is the material attenuation and/or permittivity and permeability, which are better measures of a material's ability to dampen a cavity resonance.

The most effective absorbers for cavity-resonance dampening are magnetically loaded with iron or ferrites. These materials are characterized by high permittivity and permeability plus a high magnetic loss. The base material is usually a type of elastomer, such as silicone or urethane. Commonly used materials include ECCOSORB MCS, which uses a mix of different magnetic materials to provide good performance below 2 GHz at a thickness of 0.04 in. For higher frequencies, ECCOSORB GDS (0.03 in) or ECCOSORB BSR (0.01–0.1 in) have proven effective. A common figure of merit is the attenuation expressed in decibels per centimeter. This is calculated from the measured parameters and is a useful measure of the material's absorption properties. It differs from insertion loss as it does not include reflections from mismatches at the surface of the material. The high permittivity/permeability means the energy will tend to reside inside the material (and hence away from the circuit), while the high absorption will lower the $Q$ of the cavity and, hence, the magnitude of the VSWR. Figure 4 shows the relative permittivity and permeability versus frequency of an absorber material designed for use in the microwave frequency band [2], and Figure 5 shows its attenuation in decibels per centimeter versus frequency.

As shown in Figures 4 and 5, the high permittivity, permeability, magnetic-loss tangent, and attenuation of this material make it ideal for cavity-resonance dampening applications. The real part of the relative permeability is very high ($\sim$4 at 2 GHz), while the imaginary part of the relative permeability is also high ($\sim$3 at 2 GHz), which gives the material a high degree of magnetic loss. The relative permittivity is also very high ($\sim$40), which will cause the energy to "want" to reside inside the material. Note that it is not unusual for the relative permittivity to be so much greater than the relative permeability.

Materials with only dielectric (nonmagnetic) properties can also be effective as cavity-resonance absorbers. They are less effective than the magnetic absorbers, due to the property of the electric field going to zero on a conducting wall while the magnetic field is maximum. Dielectric absorbers are generally made of a polyurethane foam material loaded with a conductive solution. Various grades are available, but, as with the magnetic absorbers, the highest value of the permittivity (real and imaginary) will give the best performance as a cavity-resonance absorber. These absorbers must also be thicker (0.125 in or more) to accomplish the same degree of dampening as a magnetic absorber, but this is sometimes offset by the fact that they are considerably less expensive. A typical dielectric absorber for this application is ECCOSORB LS-26, which is available in a range of thicknesses. LS-26 is a lightweight polyurethane-foam absorber. Foam dielectric absorbers can be a viable solution if the cavity can accommodate a thick absorber. Another issue is that they are conductive, which can be a factor if they come into contact with active devices. Spray coatings or a polyethylene film can be used to minimize this risk.

Physical parameters of interest in choosing an absorber include temperature resistance, outgassing properties, and adhesion properties. Silicone elastomers have very good high-temperature (177 °C) properties and good outgassing properties and are the most popular on the market today. Other elastomer matrices used in commercially available materials include urethane, nitrile, and neoprene.

## Thickness

Selecting the thickness of an absorber material is rather straightforward, as the resonance dampening effectiveness is directly proportional to this thickness. The effectiveness is also directly proportional to the frequency that is resonant, meaning that thinner material can be used at higher frequencies. Magnetic material at a thickness around 0.04 in in has proven to be effective in the lower microwave range (up to 10 GHz), while 0.02–0.03 in has been effective in the upper microwave range and 0.01 in for the millimeter-wave bands. A purely dielectric (i.e., not magnetic) absorber is generally not available at a thickness less than 0.125 in.

## Absorber Placement in Cavity

It is rarely, if ever, necessary to treat all the cavity walls with absorber. It is usually not even necessary to treat the entirety of one wall. Unfortunately though, analytic tools to determine the optimum absorber placement have not yet been developed, leaving the engineer with a cut-and-paste, trial-and-error method. Absorber manufacturers usually have generous sample policies for just this reason. It is difficult to determine a priori where the optimum absorber placement would be. Sometimes the absorber acts to dampen the resonance. Other times it acts to shift the VSWR peaks to a less detrimental location.

Fortunately, there are general guidelines for absorber placement. Placing the absorber at the standing wave maxima is a good place to start. Most cavities are somewhat rectangular in shape, therefore, (1) can be used to determine the possible resonant frequencies. Often, only the dominant mode must be dampened. In this case, the field is at a maximum at the midpoint of the cavity. If the problem is a second-order mode, there will be two field maxima at 1/3 and 2/3 of the way across the cavity, and this logic is easily extended to locate the maxima of still higher-order modes. Determination of $m$, $n$, and $p$ in (1) plus a knowledge of the frequency causing the problem will help determine the optimum absorber placement.

## Ease of Application

Elastomer and foam absorbers can be easily cut with a die or a razor blade. Most are available with a peel and stick pressure-sensitive adhesive (PSA). This has become the application method of choice as it eliminates the need for solvent-based material and messy adhesives. The adhesion qualities of today's PSA materials, which are usually peel-and-stick, are outstanding. For more permanent applications, an epoxy mold-in-place solution is available. For this application, the absorber matrix is an epoxy, where the material is molded directly into the cavity for a permanent solution.

## Cost

Cost is always the most important variable. At one time, most manufacturing budgets did not allow for absorber material. In fact, absorber is still sometimes considered to be something of a band-aid applied only because the engineer failed. Absorbers tend to be a cost-effective solution as opposed to reengineering a circuit board cover or relocating circuit elements to eliminate a problem.

As mentioned previously, foam dielectric absorbers are the least expensive. If a package can accommodate an absorber 1/8-in thick, and if outgassing is not an issue, these are the materials of choice. If one must use a thinner material, and/or if outgassing must be avoided, then a silicone-based, magnetically loaded elastomer is the best choice. Using a peel-and-stick PSA material is the most cost-effective means of applying the absorber. Thinner materials will cost less, so it is worthwhile to experiment with various thicknesses to determine the thinnest possible. Finally, it is also prudent to experiment with absorber placement to determine the minimum area of coverage necessary to fix the cavity-resonance problem.

## Conclusion

With frequencies of circuit operation increasing faster than circuit board cavity sizes are decreasing, cavity-resonance problems will only become more and more pervasive. Clever engineering redesigns can often be used to solve these problems, but, often, the quickest and most cost-effective solution will be the use of absorber material to dampen the resonance.

## References:

[1] R. Harrington, *Time Harmonic Electromagnetic Fields.* New York: McGraw-Hill, 1961, p. 156.
[2] *ECCOSORB MCS*, Emerson & Cuming Microwave Prods., Randolph, MA.

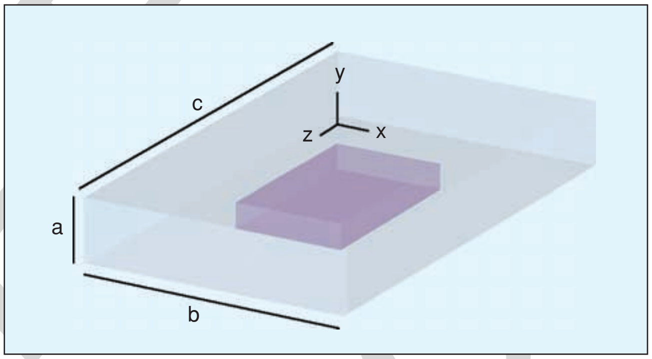

**Figure 1.** *A rectangular cavity filled with a homogeneous material.*

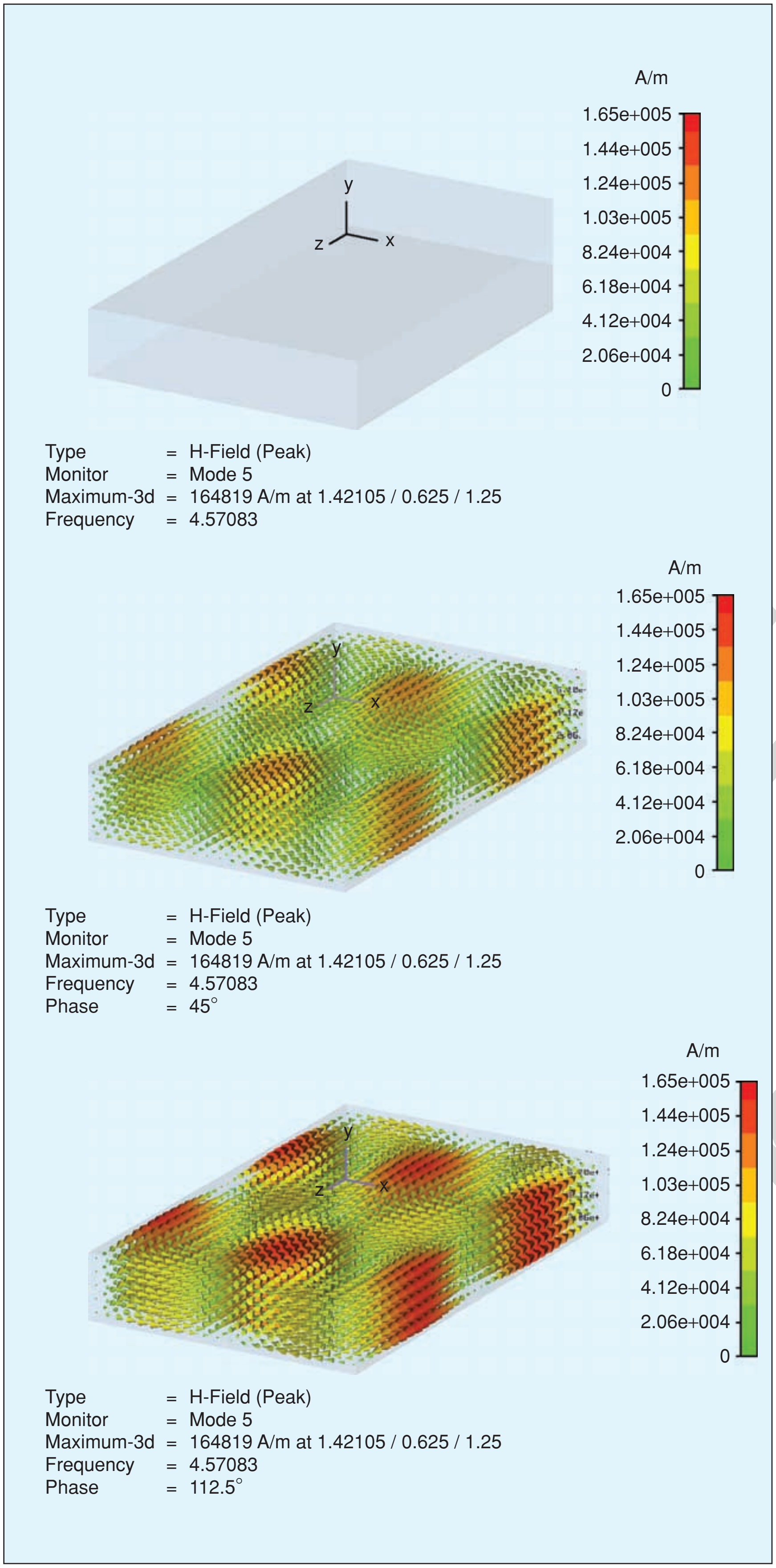

**Figure 2.** *$TE_{032}$ mode in a 3 × 5 times 0.8-in cavity with resonant frequency 4.57 GHz at (a) 0°, (b) 45°, and (c) 112.5°.*

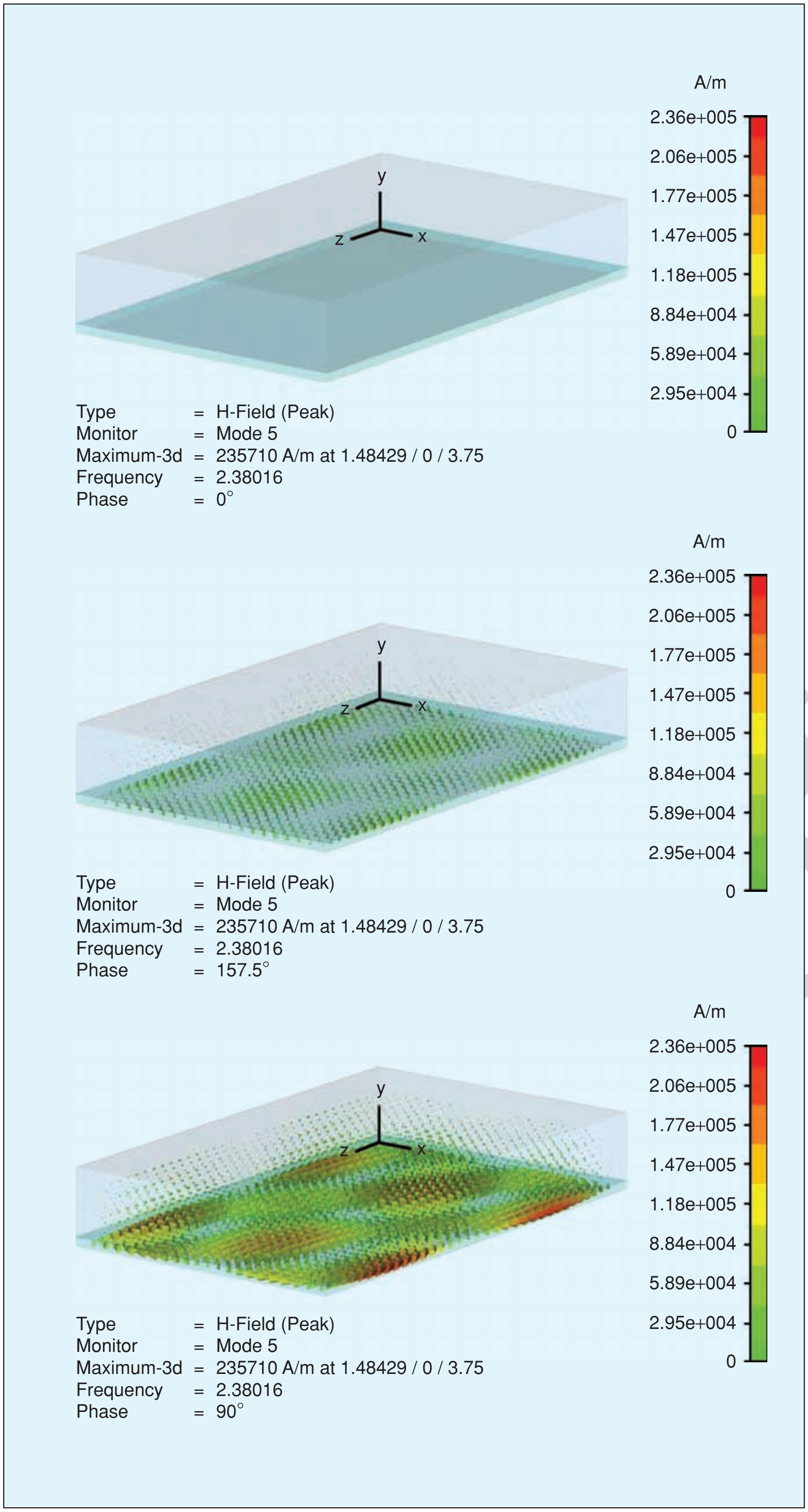

**Figure 3.** *The same cavity shown in Figure 2 but including a thin magnetically lossy absorber material.*

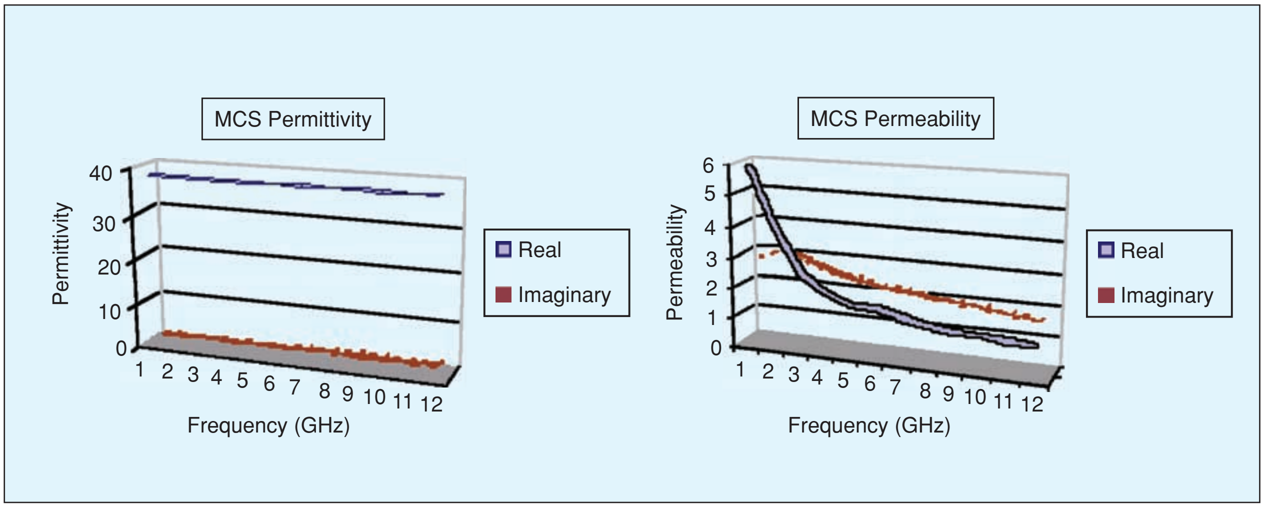

**Figure 4.** *Real and imaginary parts of the relative permittivity (left-hand plot) and permeability (right-hand plot) versus frequency of an absorber material designed for use in the microwave frequency band [2].*

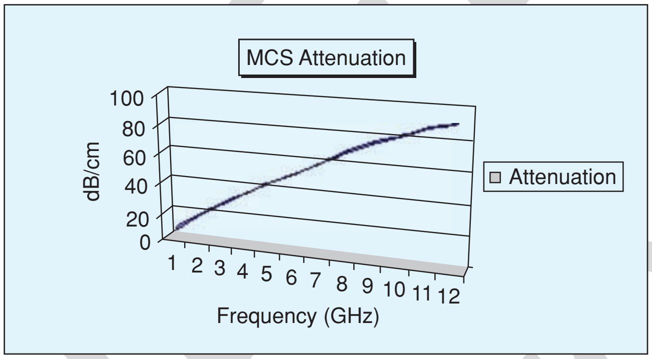

**Figure 5.** *Attenuation versus frequency of an absorber material (MCS, manufactured by Emerson & Cuming Microwave Products) designed for use in the microwave frequency band [2].*