Optimal Defect-Layer Positions in Thin Electromagnetic Energy Absorbers

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Keywords: electromagnetic heating, thermal runaway, power delivery

INTRODUCTION

High-power wireless transmission requires an effective means of converting incoming electromagnetic radiation into energy that produces useful work. One requirement of the system is the conversion of electromagnetic energy into internal energy for an absorbing material. Recent theoretical approaches to analyze composite structures have centered on layered geometries that enhance the Fabry-Bragg resonance [1]-[3]. Lossless layers surround a lossy "defect" layer, whose loss factor increases exponentially with temperature, with the permittivities of the lossless layers larger than those in the defect layer. Here, we investigate asymmetric configurations of the general $\boldsymbol{N}$-layer geometry with a single defect layer, allowing for this layer to reside in different positions. Our goal is to see how the position of the defect layer affects the efficiency of EM energy absorption.

METHODOLOGY

Consider the N-layer configuration shown in Fig. 1. A laminate system of N layers are irradiated symmetrically by a monochromatic plane wave. One layer is a lossy ceramic whose loss factor is temperature dependent, while the real part of the dielectric constant of all the layers are independent of temperature. We assume that the thickness of the entire system is sufficiently thin that the temperature in all the layers is the same constant, but unknown, value. Conservation of energy requires a balance between the energy absorbed in the laminate system and energy losses to the surrounding environment. At steady-state temperatures, this energy balance is represented by

$$P\varepsilon_d''(\boldsymbol{\theta})\|E_d\|_2^2 - B\theta = 0 \tag{1}$$

where P is the ratio of the applied electromagnetic power applied to the system balanced by characteristic thermal conduction through the system, ${\varepsilon_d}''(\theta)$ is the loss factor in the defect layer, $\theta = (T - T_0)/T_0$, where T is the system temperature and T_0 is the ambient temperature is the relative temperature difference of the system temperature and ambient with respect to the ambient temperature, and B is the Biot number representing energy losses to the

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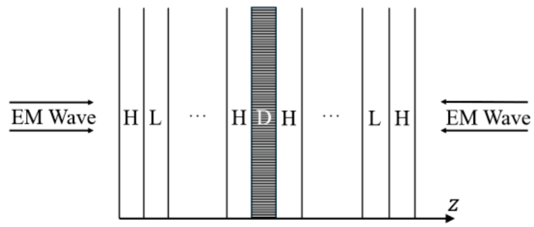

Figure 1. Diagram of a sample N-layer laminate system. Lossless layers with high permittivity are marked with an H, low permittivity marked with an L, and the defect layer is marked with a D.

environment compared to the thermal conduction in the system. $\|E_d\|_2^2$ is the L_2-norm of the electric field in the defect layer, E_d. Equation (1) is coupled with to the solution of the electric field amplitude E_d, which needs to be determined through the solution of Helmholtz's equation in each of the layers $j = 1,2, \dots, N$

$$E_j''(z) + \gamma^2 \varepsilon_j' E_j(z) = 0 \, , z_{j-1} < z < z_j \, , j \neq d \, , \tag{2}$$
$$E_d''(z) + \gamma^2 [\varepsilon_d' + i\varepsilon_d''(\theta)] = 0 \, , z_{d-1} < z < z_d \, , \tag{3}$$

where E_j is the electric field amplitude in layer j, γ is the free space wavenumber of the electromagnetic wave, scaled on the system thickness, $\varepsilon_j{}'$ is the real part of the dielectric constant in layer j, and the domain for each layer is given by $z_{j-1} < z < z_j$. Continuity of the electric and magnetic fields are applied at each of the interfaces $z_1 < z < z_{N-1}$, and Sommerfeld radiation conditions are applied at $z = z_0$ and $z = z_N$.

To solve (1)-(3), we represent the solution of (2) in the lossless layers using the transfer matrix method to represent the left- and right- travelling-wave amplitudes to find effective boundary conditions on the defect layer. With these effective boundary conditions, we then use finite difference methods in the defect layer solve for E_d using θ as a parameter. With E_d, we find the applied power P through (1) corresponding to the prescribed temperature θ.

RESULTS

Plotting equilibrium temperature against incident power yields a bifurcation diagram known as a power response curve. Power response curves and reflection coefficients for two different wave frequencies are presented in Fig. 2. The sample considered is a 7-layer system in an asymmetric H-X-HLHLH configuration, with lossless layer permittivities $\varepsilon_H' = (7\pi/2)^2$ and $\varepsilon_L' = (\pi/2)^2$, and a defect layer with $\varepsilon_d' = \pi^2$ and $\varepsilon_d'' = 10^{-3} e^{3T}$. Fig. 2(a) is a power response curve for $\gamma = 1$, featuring an additional stable branch compared to what has been observed in previous work. The reflection coefficient's plot in Fig. 2(b) shows that low reflection coefficients occur at points corresponding to the first two unstable nodes of the power response curve.

DISCUSSION

In asymmetrical geometries, like those used to generate Fig. 2, there is a subsystem on each side of the defect layer where separate resonance can take place. The objective of this work

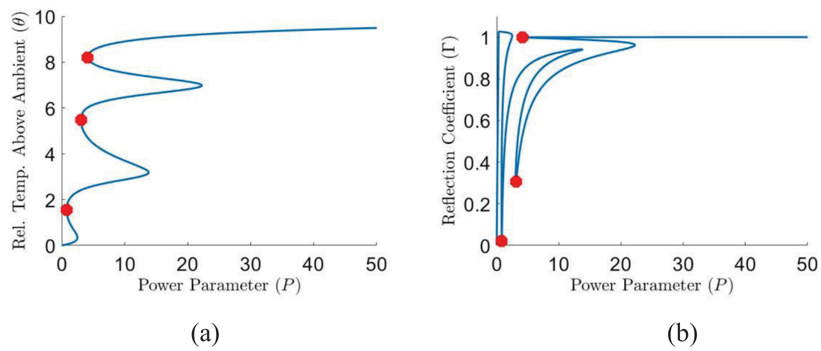

Figure 2. Power response curve (a) and reflection coefficients (b) for $\gamma = 1$. Reflection coefficient values at unstable nodes are highlighted on both graphs.

is to categorize how these pairs of resonant systems interact with the defect layer in terms of thermal response. The power response curve presented in Fig. 2 demonstrates a higher level of resonance than exhibited by previously studied systems [1], [3], possessing four branches, all of which occur at relatively low powers.

Low reflection coefficients occur at and around both the first and second unstable nodes. Hence, absorption efficiency is locally optimized near the left lower two limit points shown in Fig. 2(a).

CONCLUSION

We have shown that it is possible to achieve higher levels of resonance in a thin electromagnetic energy absorber by using asymmetric layer configurations. Placing the defect layer in an asymmetric configuration allows for the absorbing system to be operated more efficiently compared to the symmetric case. By changing the position of the defect layer, engineers can use this as a design parameter for better electromagnetic energy absorbers.

ACKNOWLEDGMENT

The authors are grateful to the Air Force Office of Scientific Research, Award FA9550-18-1-0528, for their support of this work. The author's affiliation with The MITRE Corporation is provided for identification purposes only and is not intended to convey or imply MITRE's concurrence with, or support for, the positions, opinions, or viewpoints expressed by the author.

REFERENCES

[1] J.M. Gaone, B.S. Tilley, and V.V. Yakovlev, Electromagnetic heating control via high-frequency resonance of a triple-layer laminate, *J. Engineering Math*, vol. 114, no 1, pp. 65-86, 2019.
[2] A.A. Mohekar, B.S. Tilley, and V.V. Yakovlev, A triple-layer electromagnetic heat exchanger with plane Poiseuille flow: control and local onset of thermal runaway, *IEEE J. Multiscale and Multiphysics Computational Techniques*, vol. 5, pp. 119-131, 2020.
[3] J.M. Gaone, B.S. Tilley, and V.V. Yakovlev, High-frequency homogenization for electromagnetic heating of periodic media, *SIAM J. Multiscale Modeling and Simulation*, vol. 19, no 3, pp. 1285-1309, 2021.