Research Article

Frequency-Tunable Electromagnetic Absorber by Mechanically Controlling Substrate Thickness

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In this paper, we propose a frequency-tunable electromagnetic absorber that uses the mechanical control of substrate thickness. The absorption frequency of the proposed absorber can be changed by varying the substrate thickness. In order to mechanically control the substrate thickness, we introduce a 3D-printed molding with air space. The proposed structure consists of two layers and one frame: the FR4 substrate, polylactic acid (PLA) frame, and air substrate. The FR4 and PLA thicknesses are fixed, and the air thickness is varied using the PLA frame. Therefore, the effective dielectric constant of the overall substrate can be changed. The metallic rectangular patch and ground are patterned on the top and bottom FR4 substrates, respectively. The performance of the proposed tunable absorber is demonstrated from full-wave simulation and measurements. When both of the FR4 substrate thicknesses are 0.3 mm and the air thickness is changed from 1 to 3.5 mm, the absorption frequency is changed from 8.9 to 8.0 GHz, respectively. Therefore, the frequency-tuning capability of the proposed absorber is successfully demonstrated.

1. Introduction

Metamaterials are artificial structures in which periodic unit cells are infinitely arranged. Using these metamaterials, we can control the characteristics of a material [1]. These technologies are used in various fields, such as stealth technology [2, 3], electromagnetic interference (EMI) and electromagnetic compatibility (EMC) solutions [4], superlenses [5, 6], RF circuit applications [7], and sound wave technology [8]. Metamaterial absorbers are also one of its promising applications. The metamaterial absorber was first proposed by Landy et al. [9]. The previous absorbers, such as ferrite [10–13] or wedge-tapered [14, 15] absorbers, were bulky and, therefore, were limited by space. Compared to material-based electromagnetic (EM) absorbers, structure-based metamaterial absorbers show high absorption rates, low production costs, and functionality with a low profile.

In spite of the several advantages of the metamaterial absorber, it has the disadvantage of a narrow bandwidth, because it uses electromagnetic resonance. Therefore, in order to overcome this disadvantage, metamaterial absorbers have been designed using lossy patterns [16–18], multiresonance [19–21], and lumped components [22–24], in order to broaden the absorption frequencies. A frequency-tunable metamaterial absorber is an alternative solution. The frequency-tunable metamaterial absorber can be used not only as an electromagnetic absorber but also as a frequency-selective sensor. Most frequency-tunable metamaterial absorbers have been realized using electronic devices such as diodes [25–27], microelectromechanical systems (MEMS) [28–30], and liquid crystal technology [31, 32]. Recently, fluidically tunable metamaterial absorbers have been proposed using liquid metal [33–35]. These electrically tunable devices show an instantaneous response. However, they are not only costly but also have limitations of design in a periodic structure because of additional DC bias lines and an extremely large number of devices. Alternatively, frequency-tunable metamaterial absorbers using liquid crystal or liquid metal can be fabricated not only on hard substrates but also on flexible substrates. In spite of its slow
tuning speed, this type of tunable absorbers has drawn interest due to its flexibility and simple design.

Recently, mechanically tunable metamaterial absorbers have been proposed using stretching technology [36–38]. For instance, the physical size of the unit cell can be deformed by stretching the substrate. Its tuning speed is slow, but it has a simple design and low cost for a periodic structure. Because the absorption frequency can be determined by the deformation level, a mechanically tunable absorber can be used for frequency tunability as well as physical strain sensors.

In this paper, we proposed a novel frequency-tunable EM absorber by mechanically controlling the substrate thickness. The proposed thickness-controllable substrate consists of the FR4 layer with fixed thickness and the air layer with controllable thickness. In order to mechanically control the thickness of the substrate, a polylactic acid (PLA) frame using a 3D printer was fabricated. The frequency tunability of the proposed EM absorber is successfully demonstrated through full-wave simulation and measurement.

2. Electromagnetic Absorber Design

In this paper, we proposed a rectangular patch for the unit cell of the absorber. Figure 1 shows the geometry of a unit cell of the proposed absorber with geometrical dimensions. The unit cell size ($W_s \times W_s$) is $12\text{ mm} \times 12\text{ mm}$. The proposed absorber is composed of two FR-4 substrates with the air substrate in between, as illustrated in Figure 1(b). The dielectric constant and tangent loss of the FR-4 substrate are 4.4 and 0.02, respectively. The patch is designed on the top of the upper FR-4 substrate. The ground plane is designed on the bottom FR-4 substrate. Both FR-4 substrates have a fixed thickness ($H_2$ and $H_3$) of 0.5 mm. The air substrate thickness ($H_1$) can be varied from 1.5 mm to 3.5 mm. In this work, the patch size is fixed, and the substrate thickness
is varied. In particular, when the thickness of the air substrate is varied, $H_s$ and $\varepsilon_{\text{eff}}$ are changed, thereby changing the resonant frequency.

3. Simulation Results

Figure 2 shows the simulated reflection coefficients of the proposed absorber at different air thickness of 1.5 mm, 2.5 mm, and 3.5 mm. ANSYS high-frequency structure simulator (HFSS) is used for full-wave analysis. It is observed that the resonant frequency is 8.7 GHz with a reflection coefficient of $-15$ dB when the air thickness is 1.5 mm. When the thickness of the air layer is increased to 2.5 mm and 3.5 mm, the resonant frequency decreased to 8.4 GHz and 8.2 GHz, respectively. Therefore, the resonance frequency shifted by 0.5 GHz from 8.7 to 8.2 GHz. Figure 3 shows the simulation results of the electrical field distribution and vector current density of the proposed absorber when the E- and H-fields are incident on x and y polarization, respectively.

As shown in Figure 3(a), the electrical field is distributed on an edge of the patch along the x direction, which generates an electric response. The vector current density flows in the y direction, as shown in Figure 3(b). The top and bottom planes of the vector current densities flow in the +y and –y direction, which generates a magnetic response as shown in Figure 3(c).

4. Measurement Results

For the experiment, we used a monostatic RCS measurement setup. Figure 4 shows the illustration of the monostatic far-field RCS measurement system. After the prototype is fabricated, we measured the reflection coefficient to prove the performance. The absorption is calculated by (1). Because the bottom is covered entirely by copper, there is no transmitted wave ($T$). Therefore, the absorption is calculated only from the reflection coefficient ($\Gamma$).

$$A(\omega) = 1 - \Gamma(\omega) - T(\omega) = 1 - \Gamma(\omega).$$

(1)

To measure the reflection coefficient of the prototype, we used a single WR-90 PE9856/SF-15 horn antenna (Pasternack, CA, USA). The operating frequency range is 8.2–12.4 GHz, and the nominal gain is 15 dB. The antenna far field for measurement is 0.5 meter. The back side of the prototype is placed in the wedge-tapered absorber, which prevents unexpected reflected waves. We analyzed the experiment results using an Anritsu MS2038C vector network analyzer, utilizing the time-gating function for measurement.

Figure 5 shows the 3D-printed frame for the fixed air thickness. As shown in Figure 5(a), we fabricated a PLA frame with 0.5 mm interval slots. We used the Ultimaker2+ 3D printer (Ultimaker B.V., Geldermalsen, Netherlands) for the PLA frame fabrication. Figure 5(b) shows a picture
of a fabricated absorber. The fabricated absorber size is 180 mm × 180 mm. Figure 5(c) shows the combined PLA frame and absorber.

Figure 6 shows the measured reflection coefficient according to the change in air thickness and the relation between the measurement results and fitted curve. In Figure 6(a), when the air layer thickness is 1.5 mm, the resonant frequency is 8.9 GHz with −41 dB. When the thickness of the air layer was increased from 1.5 mm to 2.5 mm and 3.5 mm, respectively, the resonant frequencies decreased from 8.9 GHz to 8.5 GHz and 8.0 GHz. Figure 6(b) shows the relation between the measurement results and fitted...
curve. From the fitted curve of $y = -0.45x + 9.519$, the sensitivity is defined to be $4.5 \times 10^8$ Hz/mm when the air layer thickness is changed. Table 1 shows the comparison between the proposed work and other papers. The proposed work shows wider tuning range and bandwidth compared to other works.

5. Conclusions

In this paper, we proposed frequency-tunable electromagnetic absorber using the mechanical control of substrate thickness. In order to control the substrate thickness, a PLA frame fabricated with a 3D printer was used as the fixed substrate thickness, mechanically. We used two FR4 substrates with a middle air layer to control the thickness of the air layer mechanically. The top side of the upper substrate is designed by patch. The bottom side of the bottom substrate is designed as ground. The patch dimension of a unit cell is $8 \times 7$ mm, and the overall fabricated absorber is $180 \times 180$ mm. To perform the measurement, we set up a monostatic RCS measurement. The measurement was performed using a WR-90 horn antenna and a network analyzer. The resonant frequency was matched to 8.9 GHz with a reflection coefficient of $-41$ dB. When the air thickness increased from 1.5 mm to 2.5 mm and 3.5 mm, the resonant frequency decreased from 8.9 GHz to 8.5 GHz and 8.0 GHz, respectively, shifted by up to 0.9 GHz. Therefore, we proved the successful fabrication of a frequency-tunable electromagnetic absorber using a mechanically controlled substrate thickness and proved the results through simulation and measurement.

Data Availability

The structures are simulated and analyzed by ANSYS HFSS (high-frequency structure simulator).

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Table 1: Comparison of the proposed mechanically frequency reconfigurable absorber with those of other papers.

| Reference paper | Tuning method                      | Tuning frequency range (GHz) | BW $^*$ (%) |
|-----------------|------------------------------------|-----------------------------|-------------|
| [38]            | Mechanically stretchable            | 11.15–11.56                 | 3           |
| [39]            | Mechanically stretchable            | 640–680                     | 8           |
| [40]            | Microelectromechanical system (MEMS) | 1280–1320                  | 3           |
| [37]            | Mechanically stretchable            | 10.4–11.0                   | 5           |
| Proposed work   | Mechanically control the substrate thickness | 8.0–8.9                    | 10          |

$^*$ $\text{BW} = \frac{\Delta f}{f_c}$, where $\Delta f = f_{\text{high}} - f_{\text{low}}$ and $f_c = (f_{\text{high}} + f_{\text{low}})/2$. 

Figure 6: Measured reflection coefficient according to change in air thickness and the relation between the measurement results and fitted curve.
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