

Ultra-thin Polarization Independent Absorber Using Hexagonal Interdigital Metamaterial

Joungyoung Lee, Young Joong Yoon, and Sungjoon Lim

An ultra-thin hexagonal microwave metamaterial absorber is described. It can absorb any polarized transverse electromagnetic wave because of its hexagonal shape. In spite of its very thin structure, almost $0.028\lambda_g$, the absorber achieved 99% absorptivity at 11.35 GHz in experimental results because of the increased coupling losses, showing good agreement with simulation results. In addition, this high absorbance is unchanged for any polarized waves with the same frequency.

Keywords: Metamaterials, frequency selective surface (FSS), absorber.

I. Introduction

The major benefit of using metamaterial is that the effective permittivity $\epsilon(\omega)$ and permeability $\mu(\omega)$ of the material can be characterized by periodically depositing metallic structures whose dimensions are much smaller than the wavelength of interest of the radiation of interest. The research on metamaterials was initially focused on the negative refractive index achieved by manipulation of the effective $\epsilon(\omega)$ and $\mu(\omega)$. Researchers have more recently been interested in matching the intrinsic impedance of metamaterials to free-space absorber applications. For example, radar absorbing material operating in varying spectral ranges from microwave to the near optical frequencies has been studied [1].

In addition, researchers are trying to obtain metamaterials with high absorption, polarization, and incident angle

insensitivity [2], [3]. In this letter, a polarization independent absorber with a very thin structure is proposed. Compared to other absorbers, which are only effective at limited polarization angles, the proposed absorber absorbs any polarized waves, while having a thickness of only $0.028\lambda_g$; this has never been achieved previously even in high-impedance surface absorber studies [4]. The thickness comparison will be shown later in this letter.

II. Theory

Absorptivity is defined as $A(\omega) = 1 - R(\omega) - T(\omega)$, $R(\omega) = |S_{11}|^2$, and $T(\omega) = |S_{21}|^2$, where $R(\omega)$ and $T(\omega)$ are the reflectance and transmittance, respectively. Thus, when $R(\omega) = T(\omega) = 0$, a perfect absorptivity ($A(\omega) = 1$) is achieved. The main concept of a metamaterial absorber starts from the careful design of a complex electric permittivity $\tilde{\epsilon}(\omega) = \epsilon_1 + i\epsilon_2$ and a magnetic permeability $\tilde{\mu}(\omega) = \mu_1 + i\mu_2$, individually. Near-zero reflectance can be achieved by matching the effective parameters $\tilde{\epsilon}(\omega) = \tilde{\mu}(\omega)$ so as to match the intrinsic impedance $Z(\omega) = \sqrt{\tilde{\mu}(\omega)/\tilde{\epsilon}(\omega)}$ to that of the free space. Due to this mechanism, which differs from the behavior of other absorbers such as those considered by Salisbury [5] and Jaumann, the metamaterial absorber does not require a substantial thickness relative to the wavelength, such as $\lambda/4$ at a center frequency. In addition, a near zero transmission can be achieved because of the large imaginary parts of the refractive index n_2 which is related to the loss in the metamaterial. Therefore, high absorptivity in a thin structure configuration can be achieved by designing the absorber to have intrinsic impedance matched to that of the free space at a point as well as having a sufficiently large imaginary component to the refractive index. Since the proposed absorber

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has a ground plate on the bottom layer, the reflected wave from the ground plate should be reduced by a thick lossy substrate in order to have high absorption. In the proposed absorber, high absorption can be achieved through the use of an interdigital configuration instead of a thick lossy substrate. Strong coupling between the digital components results in high coupling losses so that the relatively low substrate loss from the thin substrate is compensated.

III. Design

The proposed metamaterial absorber consists of two metallic layers, as shown in Figs. 1(a) and 1(b). The electrical responses were supplied by an electromagnetic resonator on the top layer in Fig. 1(a). To achieve the polarization of an independent absorber, a hexagonal resonator having a six-fold rotational symmetry around the propagation axis was designed. The interdigital capacitor pattern was introduced not only to manipulate the electrical response but also to decrease the transmittance through an increase in the coupling losses.

The resonator and bottom metallic plate were separated by the substrate and were placed parallel to each other to achieve the magnetic response, as shown in Fig. 1(c). The magnetic responses were generated between the resonator and bottom layer, where circulating currents are driven by the magnetic field of the incident transverse electromagnetic wave. The

structure of the resonator was carefully designed to satisfy the matching condition for $\epsilon(\omega)$ and $\mu(\omega)$. The optimized design was accomplished with the help of a commercial electromagnetic simulator. The dimensions of the electromagnetic resonator are indicated in Fig. 1(a).

The simulated $A(\omega)$ function was plotted from 0 (0%) to 1 (100%) over the 10-GHz to 13-GHz frequency range. As had been expected before the simulation, $T(\omega)$ remained at 0% over all the frequency range due to the effect of the conducting bottom layer, and $R(\omega)$ has a minimum value of less than 0.01 at $\omega_0=11.3$ GHz. Thus, as shown in Fig. 2, at this frequency, an almost perfect absorption [$A(\omega) = 1 - R(\omega) - T(\omega) = 1$] was obtained with a full width at half maximum (FWHM) of 4.2%. By application of the retrieval method [6], the free-space normalized optical parameters can be obtained by calculation of the S -parameters. The normalized intrinsic impedance $z(\omega)$ is defined by

$$z(\omega) = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}}. \quad (1)$$

The refractive index $n(\omega)$ is also extracted as

$$n(\omega) = \frac{1}{kd} \cos^{-1} \left[\frac{1}{2S_{21}} (1 - S_{11}^2 + S_{21}^2) \right], \quad (2)$$

where d is thickness of the substrate and k is the wave number. From (1) and (2), the relative permittivity $\epsilon_r(\omega)$ and permeability $\mu_r(\omega)$ are calculated and plotted in Fig. 3(a). In this figure, it can be observed that the real parts of $\epsilon_r(\omega)$ and $\mu_r(\omega)$ are matched to 8.2 at 11.3 GHz. Figure 3(b) shows the free-space normalized intrinsic impedance. The real part of the impedance has a value similar to the impedance of air, and the imaginary term is 0 at 11.3 GHz. Therefore, it is confirmed that the inductive resonance and capacitive resonance of the structure are matched at 11.3 GHz. In other words, it can be

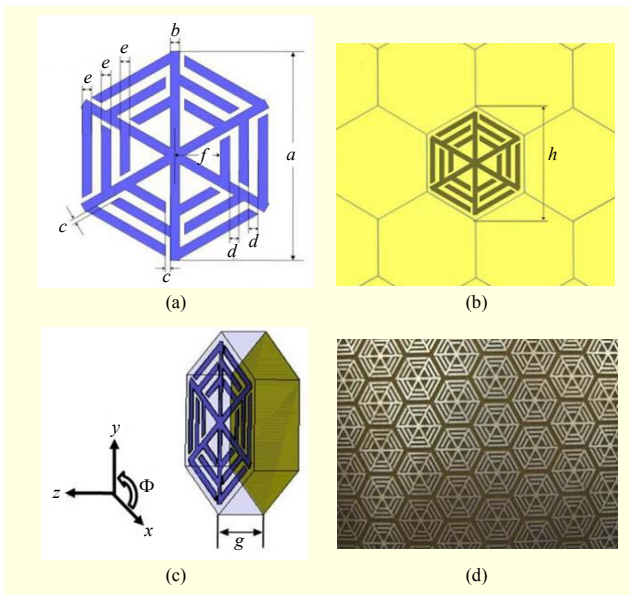


Fig. 1. Hexagonal-shape metamaterial absorber: (a) designed electromagnetic resonator with $a=8.9$, $b=0.4$, $c=0.2$, $d=0.4$, $e=0.4$, and $f=1.9$ (top layer), (b) bottom metal plate and unit cell length of electric resonator ($h=10$) on top layer, (c) prospective view of proposed metamaterial absorber $g=0.4$ (measurement units are in millimeters), and (d) photograph of fabricated absorber.

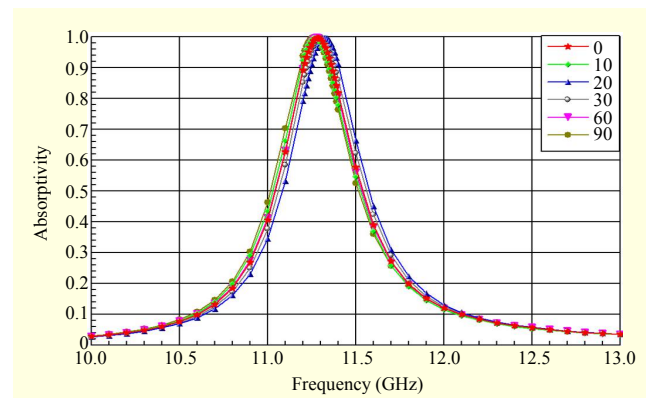


Fig. 2. Simulated absorptivity at different polarization angles Φ . Symbols for the different curves indicate the polarization angles.

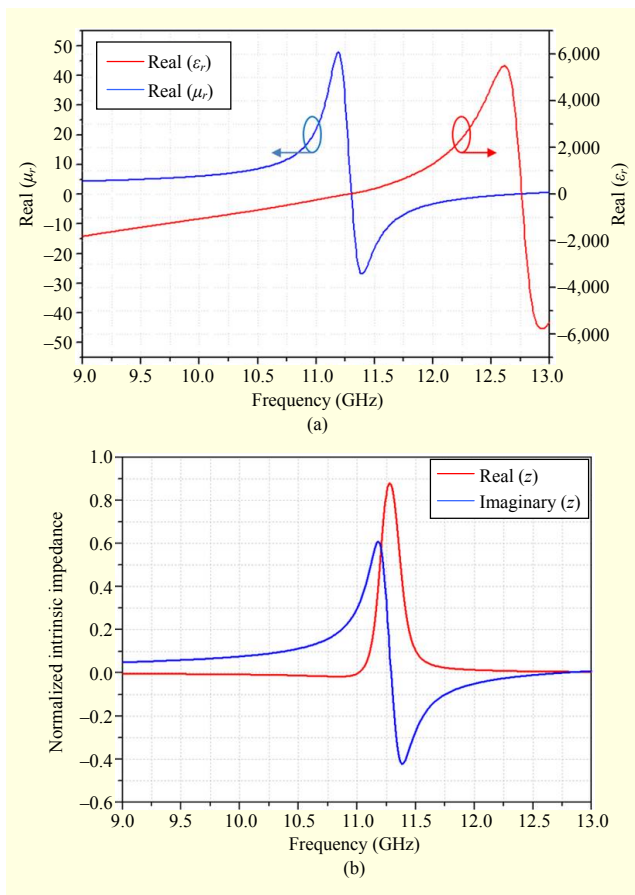


Fig. 3. Calculated (a) real term of ϵ and μ and (b) real and imaginary term of normalized intrinsic impedance.

said that the intrinsic impedance of the absorber is matched to that of air. The polarization independence of the proposed structure is demonstrated by simulating the absorptivity with different polarization states. Six polarization states (0° , 10° , 20° , 30° , 60° , 90°) were excited at 11.3 GHz. Absorptivity above 99.9% was obtained at each central frequency for all of these polarizations as shown in Fig. 2. In addition, absorptivity was found to be greater than 98% for all these polarizations at 11.3 GHz. Also, the maximum central frequency shift was less than 1% from 11.3 GHz across the range of polarization states. In addition, the proposed absorber can maintain 80% absorptivity in the range of the incident angle of $\pm 25^\circ$ at 11.3 GHz. These results are better than those of the previous absorber in [7].

IV. Fabrication

The metamaterial absorber was fabricated using an optical lithographic processes on a 0.4-mm-thick FR4 substrate with $\epsilon=3.7$ and $\tan \delta=0.02$. Each of the metal layers was modeled from 0.018-mm-thick copper with an electric conductivity of

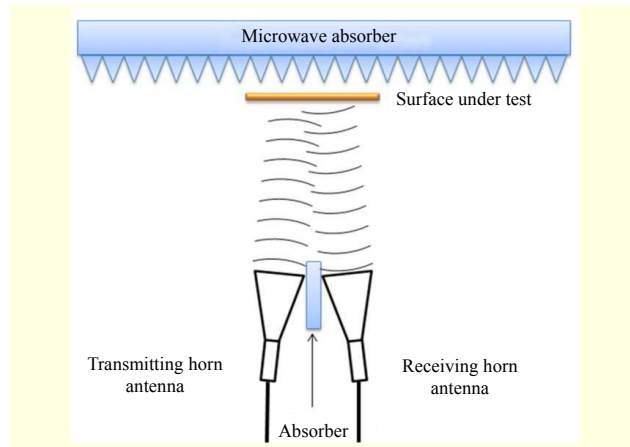


Fig. 4. Test setup to measure absorptivity.

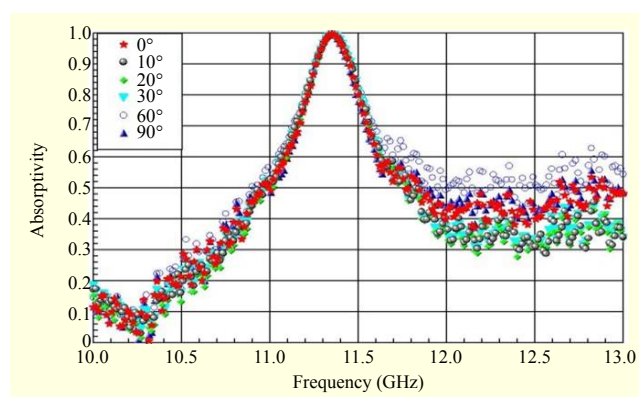


Fig. 5. Measured absorptivity at different polarization angles Φ . Symbols for different curves indicate polarization angles.

$\sigma=5.8 \times 10^7 S/m$. Although an FR4 substrate is not used in microwave bands, it is a good substrate for absorber applications because of its high dielectric loss. Low costs for material and fabrication are an additional advantage.

The simulation results were proven experimentally by measurement of the S -parameters of the periodic array of the unit cell, as shown in Fig. 1(d). The S -parameters were measured by a vector network analyzer that supplies microwaves in the range of 8 GHz to 12 GHz through horn antennas. The measurement was conducted in a microwave anechoic chamber, and its test setup is illustrated in Fig. 4. Two horn antennas were focused on the sample by facing the absorber on the same side. The timing gating function of the network analyzer is used to eliminate mutual coupling between the closely aligned two horn antennas. Then, the electromagnetic waves from the horn antennas were linearly polarized. The sample was rotated from 0° to 90° with 10° steps for the measurement of the absorber polarization insensitivity. The sample was simply replaced with aluminum as a perfect reflector for calibration of the reflection measurement. As shown in Fig. 5, the experimental results show that all peaks

Table 1. Performance comparison of metamaterial absorbers.

Absorber	Operating frequency	Thickness	FWHM	Polarization insensitivity
Proposed	11.35 GHz	0.4 mm ($0.028\lambda_g$)	4.4%	Yes
[7]	11.65 GHz	0.72 mm (N/A)	4.0%	No
[8]	10.14 GHz	1 mm ($0.068\lambda_g$)	4.7%	Yes
[9]	10.45 GHz	0.9 mm ($0.068\lambda_g$)	4.2%	No

exhibited over 99% absorption at 11.35 GHz. These results show good agreement with the simulation results, except for the small frequency shift and broadening bandwidth. The frequency deviation was due to the fabrication error from the fine interdigital lines. The broadening bandwidth discrepancy was caused by the losses at higher frequencies.

As shown in Table 1, the proposed metamaterial absorber is compared with the performance of other metamaterial absorbers. The thickness of the absorber is a remarkable result when compared to other absorbers that have also been designed to be very thin using various strategies.

V. Conclusion

In summary, the design and construction of a novel ultra-thin metamaterial absorber has been presented. Experimentally, the absorber has been found to have an absorptivity of 99% at 11.35 GHz. This performance has been achieved for all transverse polarizations because of the hexagonal shape of the absorber. High coupling losses from the interdigital capacitors reduce the substrate thickness required to achieve the high absorption.

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