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77 GHz Metamaterial Absorbers Composed of Crossed Dipoles on Grounded Dielectric Substrate for Automotive Application

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In addressing the needs of automotive radar designers, this study investigates the 77 GHz radar absorbing materials (RAMs) suitable for the automotive environment. A metamaterial structure is composed of metallic conductors of cross pattern on a grounded dielectric substrate (FR4). Computational tools (ANSYS HFSS 13.0) were used to model the interaction between electromagnetic waves and the metamaterial structures. The simulation output included the reflection coefficient. Another parameter of interest was the surface currents and electric fields, which were used to depict the resonating behavior of the metallic portions of the metamaterials. Magnetic resonance resulting from antiparallel currents between the strip conductors on front surface and ground bottom plane was observed at the frequency of minimum reflection loss (–23 dB at 77 GHz) with a small substrate thickness as low as 0.2 mm. The simulated resonance frequency and reflection loss can be explained well on the basis of the circuit theory of an *LC* resonator.

Keywords : metamaterial absorbers, automotive radars, magnetic resonance

1. Introduction

With a rapid progress in self-driving technology, which is one of the 4th industrial revolution technologies, the field of radar sensors in autonomous vehicles is recognized as a key technology to identify various objects in all driving environments. Radar sensors for vehicles primarily use the 77 GHz frequency bands to identify various objects in long range self-driving environments. With an increasing number of automotive radar sensors, electromagnetic interference (EMI) is one of the big problems when several vehicle radar sensors operate at the same frequency band or are adjacent to each other. In the event of interference, a ghost target can be created due to a duplication of transmission signal or noise floor of the radar signal can be increased, resulting in a reduction in the signal-to-noise ratio [1]. For this purpose, it is being considered to apply a radio absorber that suppress the unwanted signals in the area of concern.

To address these problems, the introduction of metamaterials can be considered with their advantage of excellent electromagnetic wave absorbing properties, having extremely small thickness and design flexibility over a broad frequency range, from microwaves to optics [2-6]. In a three-layer planar metamaterial structure, magnetic coupling is achieved via antiparallel currents in the conductor on the top layer and the ground conductor on the bottom layer, which is enhanced as the dielectric substrate becomes thin. At the magnetic resonance frequency, each unit cell gives an approximate Lorentz oscillator response and thus permits control over two complex parameters (permeability and permittivity) leading to impedance matching, resulting in a perfect absorption at a very small substrate thickness [7-9]. That could be the novelty of the metamaterial absorbers over existing commercial particulate composites for 77 GHz absorbers [10, 11].

In this study, radar absorbing properties were investigated in a metamaterial structure composed of metallic conductors of cross pattern on a grounded dielectric substrate, for the aim of a very thin perfect absorber focusing on the automotive radar frequency. Magnetic resonance resulting from antiparallel currents between the strip conductors on front surface and ground bottom plane was observed at the frequency of minimum reflection loss (–23 dB at 77 GHz) with a small substrate thickness as low as 0.2 mm. The simulated resonance frequency and reflection loss can be explained on the basis of the circuit theory of an *LC* resonator. Better insight into the absorp-

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tion mechanism of metamaterial absorbers can be attained through the parametric analysis on reflection loss.

2. Design and Simulation

Figure 1(a) shows the structure of a metamaterial absorber (MA) composed of cross strip (CS) on the top layer and ground plane (GP) on the bottom layer separated by dielectric substrate, which is illuminated by an electromagnetic wave with wave vector k and electric field (E) and magnetic field (H) polarized parallel to the plane of the substrate. In the metamaterial design, many other patterns, such as patch, square loop, and fractal, etc, can be used. However, in the high-frequency region of 77 GHz, it was found that the cross strip is the most potential pattern based on our preliminary study. The dimensions of the unit cell (periodicity p = 2.0 mm) and CS (length d = 0.8-1.2 mm, width w = 0.05-0.3 mm) are given in Fig. 1(b). The substrate material is FR4 with dielectric permittivity $\varepsilon_r = 4.1 - j0.03$ and its thickness was varied in the range t_{FR4} = 0.1-0.5 mm. The metal on the top and bottom layer is copper with electrical conductivity $\sigma = 5.8 \times 10^7$ S/m and thickness t_m = 0.35 μm.

A computational tool (ANSYS HFSS 13.0) was used to simulate the reflection coefficient and the distribution of surface currents and electric fields, which are used to predict the resonating behavior of the MA. Since the structure is terminated by metal ground plane, the transmission is zero. HFSS is a commercial finite element method solver for electromagnetic structures from periodic arrays. Modelling and running sequence are to draw the structure, specify material characteristics for each object, and identify ports and special surface characteristics (boundary conditions). In this study, master-slave periodic boundary conditions were applied in the numerical model to mimic a 2D infinite structure. Floquet ports were used for the excitation of the periodic structure. HFSS then generates the necessary field solutions and S-parameters.

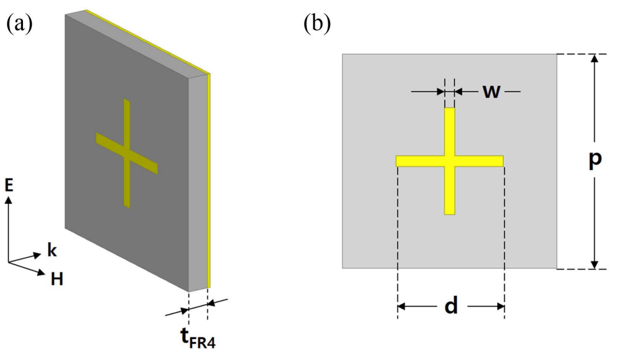

Fig. 1. (Color online) Illustration of metamaterial absorber with cross strip: (a) layer structure and (b) unit cell dimension.

3. Results and Discussion

3.1. Magnetic resonance between conductor pair

Simulation result of reflection loss is presented in Fig. 2 for a metamaterial structure with a unit cell periodicity (p = 2.0 mm), cross strip (w = 0.1 mm, d = 1.0 mm), and substrate (t_{FR4} = 0.2 mm). Reflection loss depicts the minimum value of –23 dB at 77 GHz. Fig. 3(a) presents the current density distribution in the CS and GP at 77 GHz. Antiparallel current is clearly shown in the CS conductor on the top layer and the GP conductor on the

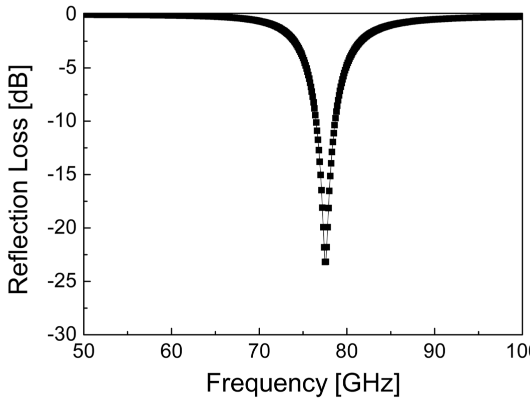

Fig. 2. Reflection loss simulated in metamaterial absorbers composed of cross strip (CS) on grounded FR4 substrate with an optimized geometry (p = 2.0 mm, w = 0.1 mm, d = 1.0 mm, t_{FR4} = 0.2 mm).

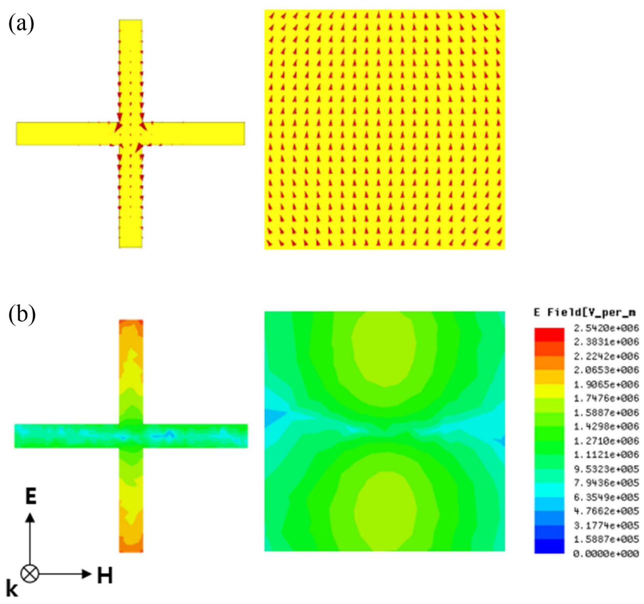

Fig. 3. (Color online) Field distribution in the cross strip (CS) and ground plane (GP) at the magnetic resonance frequency of 77 GHz: (a) current density and (b) electric field.

bottom layer, as depicted in Fig. 3(a). An incident time-varying magnetic field parallel to two separated conductors may produce to these antiparallel currents, thus yielding a Lorentz-like magnetic response [12]. Wave reflection is minimized at this magnetic resonance frequency through impedance matching between two complex parameters, electric permittivity (ε_r) and magnetic permeability (μ_r). The electric field is strong at the edge of the CS, due to local charge accumulation by circulating currents, as shown in Fig. 3(b).

The magnetic resonance frequency (f_m) is given by $f_m = 1/2\pi\sqrt{LC}$ and is inversely proportional to the inductance (L) and capacitance (C) of the CS-GP pair. The length of the magnetic resonator is equal to the CS length (d). Since the electric field is confined mainly to the edge of the CS, the effective length for capacitance between CS and GP is reduced to 0.1d [7]. The magnetic resonance frequency is calculated to be f_m = 75 GHz, which is nearly consistent with the simulation result for absorption frequency, using the values $L \cong \mu\left(\frac{dt_{FR4}}{w}\right) = 2.512 \times 10^{-9}$ [H], $C \cong \varepsilon w(0.1d)/t_{FR4} = 1.815 \times 10^{-15}$ [F]. Inductance equation is for the loop bounded by two biplanar flat conductors given in the literature [13]. Capacitance was calculated by a conventional capacitance equation for two parallel flat conductors, modifying the effective length [7]. Magnetic permeability and dielectric permittivity of FR4 substrate are given by $\mu = \mu_0 = 4\pi \times 10^{-7}$ H/m and $\varepsilon = \varepsilon_0\,\varepsilon_r = 8.854 \times 10^{-12}\,(4.1 - j0.03)$ F/m, respectively, where μ_0 and ε_0 are the permeability and permittivity of vacuum.

3.2. Parametric analysis of reflection loss

Figure 4 shows the variation of reflection loss with the CS geometry and the thickness of the substrate. The reflection loss with increasing CS length (d), from 0.8 mm to 1.2 mm, is shown in Fig. 4(a). Since both the inductance and capacitance are proportional to CS length, the magnetic resonance frequency (absorption frequency band) shifts to a lower frequency with the increase of CS length. Reflection loss is less than –20 dB, depicting almost 100 % power absorption.

On the other hand, the absorption frequency band is less sensitive to CW width (w), as shown in Fig. 4(b). As the CS width increases, increasing capacitance between the CS and GP makes the resonance frequency shift slightly to a lower frequency band and also increase the reflection loss, due to deviation from impedance matching. The minimum refection loss (–23 dB at 77 GHz) is obtained at w = 0.1 mm.

Figure 4(c) shows the effect of substrate thickness (t_{FR4}) on reflection loss. Reflection loss is minimum at t_{FR4} = 0.2 mm with an impedance matching. With respect to this matching thickness, reflection loss increases at a lower thickness (t_{FR4} = 0.1 mm) and a larger thickness ($t_{FR4} \geq 0.3$ mm). On the while, the shift of absorption frequency is confined within a small band, because increasing L and decreasing C is compensated with increasing the substrate thickness.

The magnitude of reflection loss is determined by the input impedance of the high impedance surface (Z_H), which is a parallel circuit of the input impedance of the

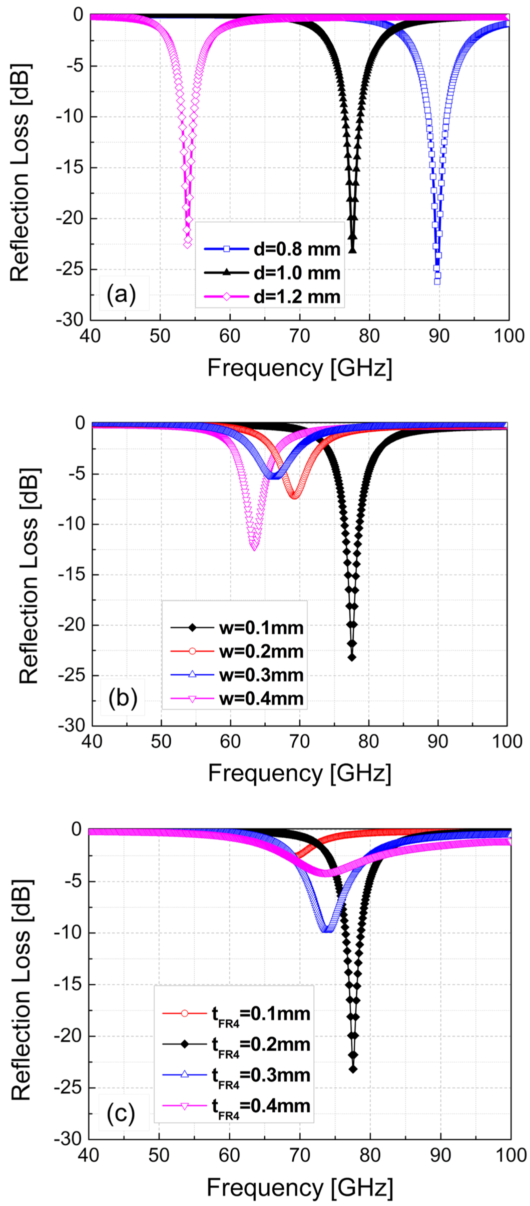

Fig. 4. (Color online) The simulation results of reflection loss with variation of geometry: (a) CS length (d = 0.8-1.2 mm, w = 0.1 mm, t_{FR4} = 0.2 mm), (b) CS width (d = 1.0 mm, w = 0.1-0.3 mm, t_{FR4} = 0.2 mm), (c) substrate thickness (d = 1.0 mm, w = 0.1 mm, t_{FR4} = 0.1-0.5 mm).

grounded substrate (Z_t) and the complex impedance of the CS-GP pair ($Z_{CS\text{-}GP}$), expressed as,

$$\frac{1}{z_H} = \frac{1}{z_d} + \frac{1}{z_{scw}} = \frac{1}{z_0[Z(Re) + jZ(Im)]} \quad (1)$$

$$Z_t = j\frac{z_0}{\sqrt{\varepsilon_r}}\tan\left(\frac{2\pi t_{FR4}}{\lambda}\sqrt{\varepsilon_r}\right) = Z_0[Z_t(Re) + jZ_t(Im)] \quad (2)$$

$$Z_{CS-GP} = R + j\left(\omega L - \frac{1}{\omega C}\right) = Z_0[Z_{CS-GP}(Re) + jZ_{CS-GP}(Im)] \quad (3)$$

where, $Z(Re)$ and $Z(Im)$ are the real and imaginary parts of the input impedance of the high impedance surface normalized by free space impedance (Z_0 = 377 Ω), λ is the wavelength in free space, and R is the resistive component of $Z_{CS\text{-}GP}$. Perfect absorption can be obtained at the impedance matching condition, given by $Z(Re) = 1$ and $Z(Im) = 0$.

The design parameters for impedance matching are substrate thickness (t_{FR4}), width (w) and length (d) of CS conductor, which influence input impedance of the grounded substrate (Z_t) and the complex impedance of the CS-GP pair ($Z_{CS\text{-}GP}$). A quantitative analysis on impedance matching concerned with the various design parameters is a complex problem. Qualitatively, based on previous study [14], the imaginary part of complex impedance of the CS-GP pair is negative ($Z_{CS\text{-}GP}(Im) \leq 0$) above the resonance frequency, showing the circuit is capacitive. Since the input impedance of the grounded substrate is inductive ($Z_t(Im) \geq 0$), total imaginary impedance can be zero ($Z(Im) = Z_{CS\text{-}GP}(Im) + Z_t(Im) = 0$) at the frequencies of optimized design parameters (w = 0.1 mm, d = 1.0 mm, t_{FR4} = 0.2 mm). At that frequency, if the real part of complex impedance of the CS-GP pair is equal to free space impedance ($Z_{CS\text{-}GP}(Re) = 1$), leading to impedance matching, and perfect absorption results.

In the case of w and t_{FR4} variation, the $Z_{CS\text{-}GP}(Re)$ deviates from free space impedance ($Z_{CS\text{-}GP}(Re) \neq 1$), resulting in lower power absorption. Similar results can be found in the microwave region [14]. On the other hand, in the case of d variation, the matching condition could be maintained at each resonance frequency (which is sensitively dependent on the frequency), resulting in lower values of reflection loss.

4. Conclusion

Radar absorbing properties were investigated numerically in a metamaterial absorber composed of cross strip on grounded dielectric substrate, focusing on the automotive radar frequency (77 GHz). Magnetic resonance resulting from antiparallel currents between the strip conductors on front surface and ground bottom plane was observed at the frequency of minimum reflection loss (–23 dB at 77 GHz) with a small substrate thickness as low as 0.2 mm. The absorber thickness is quite small as compared with that of conventional particulate coposites [11, 12], which is due to the magnetic coupling between front conductor and ground plane enhanced at a small substrate thickness. The simulated resonance frequency and reflection loss can be explained well on the basis of the circuit theory of an LC resonator. Better insight into the absorption mechanism of metamaterial absorbers can be attained through the parametric analysis on reflection loss. For experimental demonstration of our design, free space measurement is necessary, which requires a further study to fabricate a prototype sample of about 20 cm × 20 cm size using the lithography process.

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