Polarization and Incidence Angle Independent Low-Profile Wideband Metamaterial Electromagnetic Absorber Using Indium Tin Oxide (ITO) Film

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Abstract: We use indium tin oxide (ITO), one of the representative resistive materials, for the implementation of a metamaterial electromagnetic (EM) absorber with a high absorbance in a wide frequency range. Highly symmetrical split ring resonators made of ITO film are deposited on the polyethylene terephthalate with transparent and flexible features, and such a configuration causes the proposed absorber to be insensitive to polarization and incidence angles. The proposed absorber, with a profile of only 0.171\(\lambda\), exhibits a wideband absorbance of 7.2 GHz to 27 GHz, with a 90% absorption criterion. A prototype is built, and all the computed expectations from the full-wave EM simulations in this work are verified experimentally.

Keywords: indium tin oxide; resistive material; optical transparency; split ring resonator; polarization independency; incidence angle independency; metamaterial absorber; wideband; low profile

1. Introduction

A study of electromagnetic (EM) shielding absorbers is actively carried out, along with an investigation of the increase in undesirable EM radiation interference from an explosive growth of wireless devices, the high integration of electric equipment in automobiles, and several small radio stations. Furthermore, the EM absorbers can be effectively utilized to reduce the radar cross-section (RCS) in future electronic warfare, where many electronics are intensively engaged in information aggregation, engagement, and operations of surveillance and reconnaissance. There are commonly desired features for EM absorbers in either modern electronics systems or for a military purpose. From a performance perspective, a wide operating frequency range and the orientation independency of the absorber are essential, since the frequency, polarization, and incidence angle of the interference radio wave are generally unknown [1]. In addition, a planar, or thin profile form factor, is desirable compared to the commonly used bulky triangular pyramid shapes, since only a minimum footprint would be allowed for the absorbers due to the miniaturization and high integration development trend of electronics. Such a thin profile is favorable not only for electrical stealth but also for physical concealment in military vehicles [2]. However, it is challenging to achieve all the listed characteristics from conventional microwave absorbers.

Metamaterial (MTM) is an engineered periodic structure made of sub-wavelength unit cells, and it shows a frequency response that does not exist in nature, such as negative permittivity, negative permeability, or both. Such a feature is now widely used in various applications of antennas and high-frequency circuits, from microwave to THz frequency ranges [3–16]. Its artificial characteristic causes the device to show an improved performance, one that has not been possible while using a material with ordinary frequency responses. Additionally, a wide range of research has recently been conducted on MTM-based EM-absorbing structures [17–28]. However, since MTM structures are
bound to exhibit frequency-dependent responses, techniques that use a multi-layer pyramid shape [21], lumped elements [22], and resistive films [23–28] have been proposed as a means of widening the operating frequency range of MTM–EM absorbers. Among these, the multi-layer MTM absorber should have a thick profile, and a lumped elements-based MTM absorber is generally harder to fabricate; these features can be thought of as disadvantages in terms of ease of use and realization, respectively. In comparison, resistive film-based MTM absorbers have a relatively thin profile, and an easier form factor to build and handle. Representative resistive materials that can be used in absorbing structures may include indium tin oxide (ITO) and antimony tin oxide (ATO), with ITO chosen more often due to its comparatively higher transparency [29]. This is because transparent absorbers are more suitable for displays, mobile phones, and the glass windows of military vehicles [30,31].

In this work, we propose extremely thin, wideband, ITO-based MTM–EM absorbers using split ring resonators (SRRs). This reveals an improved bandwidth ratio over the structure profile when compared to reported works in the literature. It also achieves orientation independence from the polarization of the incoming EM wave due to the symmetric shape of the used SRRs. The design procedure and working mechanism of the proposed structure are explained by the numerical calculation results using the CST Studio Suite. The prototype is built, and all full-wave EM simulations are verified experimentally.

2. Absorber Design

2.1. Configuration

The unit cell configuration of the proposed EM absorber is shown in Figure 1. The top layer of the unit cell is the same variation as in the SRR structure. The SRR configuration is chosen as it can be designed symmetrically, and the number of resonances can be straightforwardly added by the number of resonators. The top and bottom layers are comprised of an ITO film, with a surface resistance of 15 ohm/m$^2$ and 10 ohm/m$^2$, respectively. They are coated on a polyethylene terephthalate (PET) with $\varepsilon_r = 3.2$ and $\tan\delta = 0.003$, and a thickness ($t$) of 0.175 mm. The target resonant frequency of the unit SRR can be expressed as:

$$f = \frac{c}{4.2r_n \cdot \sqrt{\varepsilon_r}}$$

(1)

where $r_n$ is the radius of each SRR ($n = 1, 2, 3, \text{and } 4$), $c$ is the velocity of the light, and $\varepsilon_r$ is the relative permittivity of the substrate [32]. Therefore, the resonant frequency of the unit cell, and thus the absorber, can be adjusted and calculated with its diameter. The resonant frequency of the SRR unit with the largest ($r_4 = 7.5 \text{ mm}$) and smallest diameter ($r_1 = 1.5 \text{ mm}$) is 5 GHz and 25 GHz, respectively. The quality factor for each resonance could be lower than that of normal dielectrics due to the higher loss of the ITO films, resulting in wider operating frequencies, even though only four different SRR sizes are in place. In other words, additional rings would expand the lowest operating frequency even lower, at the expense of the increased size of the unit cell. The ITO film coated at the bottom works as a ground plane with lower resistivity. As can be seen from Figure 1a, the proposed SRR takes a symmetrical form, and it makes the absorber insensitive to the polarizations and incidence angle of the incoming EM wave. The top and bottom layers are separated by a 3 mm air gap ($t_d$). The thickness of the absorber is 3.35 mm, or 0.171$\lambda$ ($2t + t_d$).
onances, as they are strongly related to effective permittivity. The impedance can be determined by the proper combination of the electrical and magnetic properties of the absorber surface. Provided that the absorber presents in free space, it is indispensable, and it can only be obtained from perfect impedance matching between the air and the absorber surface. For this reason, the reflectionless transmission characteristic is indispensable.

2.2. Current Distribution and Surface Power Loss

The incoming EM wave decays with the loss of the ITO film after it transmits through the absorber surface. The working frequency range includes part of the C-band, X-band, Ku-band, and K-band. The proposed unit cell design for the MTM absorber is shown in Figure 1a. The design parameters are: width of PET $w = 15$, radius of inner circle $r_1 = 1.5$, radius of second circle $r_2 = 3.5$, radius of third circle $r_3 = 5.5$, radius of fourth circle $r_4 = 7.5$, gap $g = 1$, $g_d = 1$, $t = 0.175$, and $t_d = 3$. All units are in millimeters.

The frequency response of the absorber is calculated using the full-wave electromagnetic simulator, CST Studio Suite, when the proposed unit cell structure is that of an infinite array. The absorbance ($A$) is calculated as:

$$A = 1 - R - T \ (\text{dB})$$

where the reflection coefficient $R$ is $S_{11}$, and the transmission coefficient $T$ is $S_{21}$, with Port 1 and Port 2 being the input and output faces of the absorber, respectively, as shown in Figure 1b. Theoretically, a perfect absorbance is achieved when $R$ and $T$ are both zero [20]. The simulated $A$, $R$, and $T$ of the proposed absorber are plotted in Figure 2, with the TM mode (or z-polarized) of the incident wave in the normal direction. It is found that absorbance above 90% is achieved across the frequency range of 7.2 GHz to 27 GHz. The fractional bandwidth is 115.8%, with a center frequency of 17.1 GHz where the maximum absorbance of 99% is observed. At a low level of transmittance in the operating frequencies, it is confirmed that the bottom layer, made of a relatively lower resistivity than the top part, works as a ground plane. The working frequency range includes part of the C-band, X-band, Ku-band, and K-band.

![Figure 1](image1.png)

**Figure 1.** Proposed unit cell design for the MTM absorber. (a) Top view, and (b) Side view. Design parameters: $w = 15$, $r_1 = 1.5$, $r_2 = 3.5$, $r_3 = 5.5$, $r_4 = 7.5$, $g = 1$, $g_d = 1$, $t = 0.175$, and $t_d = 3$. All units are in millimeters.

![Figure 2](image2.png)

**Figure 2.** Simulated results of the proposed absorber.

**2.2. Current Distribution and Surface Power Loss**

The incoming EM wave decays with the loss of the ITO film after it transmits through the absorber surface. For this reason, the reflectionless transmission characteristic is indispensable, and it can only be obtained from perfect impedance matching between the air and absorbing surface, provided that the absorber presents in free space. The surface impedance can be determined by the proper combination of the electrical and magnetic properties.
resonances, as they are strongly related to effective permittivity ($\varepsilon_{\text{eff}}$) and permeability ($\mu_{\text{eff}}$), such as $Z(w) = \sqrt{\frac{\mu_{\text{eff}}}{\varepsilon_{\text{eff}}}}$. In Figure 3, the surface current distributions at 8.35 GHz, 18.65 GHz, and 21.65 GHz—where an absorbance near 100% is observed—are plotted. At all frequencies, it is commonly seen that the current density on the top layer is relatively higher than that on the bottom layer. It is also found that the current from the top and bottom layers flows in the opposite direction at 8.35 GHz and 18.65 GHz, whereas it flows in the about same direction at 21.65 GHz. The current distribution on the top layer itself causes electrical resonance, and the current distributions at the top and bottom layers together create a current loop that results in a magnetic resonance [23]. Thus, it can be said that the surface impedance is adjusted by both the electrical and magnetic resonances at 8.35 GHz and 18.65 GHz, whereas it is predominantly controlled by an electrical resonance at 21.65 GHz. This explains why a stronger current density is formed at the top at 21.65 GHz when compared with the other two frequencies.

Next, the surface power loss density both at the top and bottom layer is simulated and plotted at the same frequencies as those shown in Figure 4. It is clearly observed that most losses occur in the top layer of the structure. From Figures 3 and 4, it is seen that the top...
layer of the absorber plays a core role in impedance matching, as well as the decaying of the wave at the absorber. As such, the parts in the SRRs where the current distribution for the resonance occurs and higher power loss density is found generally agree with each other. Since the current distribution differs on the SRR by frequency, the operating frequency could be simply tuned by its dimension.

We also study the current distribution and the surface power loss at 2 GHz, where a very low absorbance of around 10% is observed. First, it is observed from the low surface current density plot at the top layer that neither electrical resonance nor magnetic resonance occur at this frequency, as shown by Figure 5a. This means impedance matching cannot be completed at all at this frequency. This naturally leads to a very low surface power ohmic loss at the surface, as shown in Figure 5b. This study supports the idea that MTM–EM absorbers can be categorized as a band-pass frequency selective surface filter. In other words, the frequency range matched to the free space impedance of 377 Ω allows the incoming wave to pass through the absorbing surface, while the waves at all other frequencies are rejected. The proposed absorber operates as a function of the reflection coefficient with nearly zero transmittance, because the bottom layer acts like a ground plane.
plane. For this reason, a frequency with a low absorbance means that most of the incoming wave to the absorber is highly reflected. Such a reflected wave cannot be involved in the absorption process; the frequency with low absorbance shows no surface loss in ITO, which is heavily related to absorption.

Figure 5. Study of the frequency of 2 GHz with a low absorbance. (a) Surface current distribution, and (b) surface power loss.

2.3. Incidence Angle and Polarization Dependence

The proposed design holds a highly symmetric configuration, and should have strong independence from the polarization and incidence angles of the incoming EM wave to the absorber. The calculated absorbance rates for the various polarizations and incidence angles are plotted in Figure 6. Again, this is simulated when the unit cell of the proposed absorber is set as an infinite array. First, the absorbance is calculated when the absorber is rotated along $\phi$—from $0^\circ$ to $90^\circ$—with the incoming TEM plane wave. As expected, the absorbance does not change at all but stays the same because of the perfect symmetric configuration of the SRRs. In Figure 6b,c, the absorbances are compared when TE and TM mode waves are incoming; the TE mode polarization is made by rotating the absorber along the $E$-axis, as shown in the inset of Figure 6b, with the TEM incoming wave. The TM mode polarization is made via the same method, but, this time, the absorber is rotated along the $H$-axis, as shown in the inset of Figure 6c. In both cases, $\theta$ changes from $0^\circ$ to $30^\circ$. Overall, a steady absorbance is observed at wide operating frequencies, with a little degradation of up to 80% in frequencies over 25 GHz. This is because the surface impedance seen from the incoming wave is deviated from 377 ohm as $\theta$ increases, resulting in a higher reflection.
Figure 6. Simulated absorbance. (a) For various polarizations (TEM mode), (b) for various incidence angles (TE mode), and (c) for various incidence angles (TM mode).

3. Experimental Validation

A prototype of the absorber is built with a dimension of $150 \times 150 \times 3.35 \text{ mm}^3$ that is composed of a $10 \times 10$ array of the proposed unit cells, as shown by the photos in
Figure 7. The top and bottom ITO layers are separated by a supporter printed from a stereolithography (SLA) 3D printer using photopolymer standard resin from Formlabs. This physically provides the air gap shown in Figure 1b. As shown in Figure 7, the supporter is printed to have the same 3 mm thickness as the air gap, and only a minimal area of the ITO-deposited PET is attached to the supporter to minimize any possible changes stemming from the material characteristic of the supporter. The SRR patterns made of ITO are etched on a PET film using a laser ablation technique, which is the physical removal of materials by collecting a laser pulse. In this fabrication, a pulse laser with a 1064 nm wavelength and 60 µm pulse size with 15 W output power was used. The side view is shown in Figure 7b.

Photos of the measurement setup are shown in Figure 8. With the built prototype in front of the commercial pyramidal absorbers, as shown in the photos, its performance was measured using horn antennas with an operating frequency of 1–18 GHz and 18–27 GHz, respectively, to test the entire wideband absorbance frequencies of the proposed design from 7.2 GHz to 27 GHz. Note that the horn antenna was placed close to the proposed absorber to present clear photos of the measurement setup, but they were separated by 2 m when carrying out the measurement to satisfy the far-field condition. As shown in Figure 8a, the absorption rate according to the polarization angle $\phi$ was measured by rotating the proposed absorber by 0°, 45°, and 90°. This realizes the case described in Figure 6a. The measurement setup in Figure 8b shows the setup for measuring the absorbance according to the incidence angle of the TE mode (i.e., the case of Figure 6b). The same two horn antennas are positioned based on the difference in the angle of $\theta$ according to the protractor on the ground. The measurement is then carried out by varying $\theta$ from 0° to 30° by 15°. The TM mode measurement, in the case of Figure 6c, is made by rotating the horn antennas by $\phi = 90^\circ$. A copper plate is measured first, instead of the proposed absorber, for use as a reference. It is then subtracted from the measurement result of the proposed absorber. In this manner, any possible noise and destructive influence from the measurement environment can be excluded.
Figure 8. Measurement setup. (a) For various polarizations, and (b) for various incidence angles (TE and TM modes).

In Figure 9, the measured results are plotted with dots. The simulation results from Figure 6 are re-plotted as a reference. It can first be observed that the measured absorbance is not sensitive to the polarization and incidence angles because of the high symmetry of the proposed structure, such as the computed expectations for all measurements. In Figure 9a, the measurement results also reveal a high absorption rate of over 90% from 6.5 GHz to 27.3 GHz, and a fractional bandwidth of 123.1% with a reference central operating frequency of 16.9 GHz, which is slightly wider than for 7.2 GHz to 27.0 GHz (115.8%), as noted in the simulation. A deviation in the bandwidth and frequencies lower than 5 GHz may be caused by a loss in the built prototype due to the glue used in attaching the PET and the supporter, and the dielectric loss of the supporter; neither were considered in the simulations. Nevertheless, the measured results show a wide-operating bandwidth, as designed, with an insensitive characteristic to the incidence angles and polarizations.
Figure 9. Measurement setup. (a) For various polarizations, (b) for various incidence angles (TE mode), and (c) for various incidence angles (TM modes).
Lastly, the performance of the proposed absorber is compared with previously reported ITO-based EM absorber designs in terms of fractional bandwidth and thickness in Table 1. A figure-of-merit (FOM) was set to be the fractional bandwidth over the electrical thickness. As seen, the proposed work exhibits the highest FOM when compared to other published works.

Table 1. Comparison table of the ITO film-based absorber. The values from the measurement are marked with an asterisk. The values without the asterisk are from the simulation. All works in this table are transparent. The figure-of-merit is calculated as the ratio of the fractional bandwidth to the electrical thickness.

| Reference | Center Frequency [GHz] | Fractional Bandwidth [GHz] | Thickness [mm] | Figure-of-Merit |
|-----------|-------------------------|-----------------------------|----------------|-----------------|
| [24] *    | 10.33                   | 8.10 (78.4%)                | 5.35 (0.184λ)  | 425.6           |
| [25] *    | 2.64                    | 2.06 (78.0%)                | 17.10 (0.150λ) | 518.5           |
| [26]      | 11.50                   | 15.40 (133.9%)              | 8.6 (0.330λ)   | 406.2           |
| [27] *    | 9.45                    | 11.18 (118.3%)              | 6.40 (0.202λ)  | 586.8           |
| [28]      | 18.40                   | 20.60 (112.0%)              | 3.30 (0.202λ)  | 553.1           |
| This work * | 16.90                   | 20.80 (123.1%)              | 3.35 (0.197λ)  | 624.2           |

4. Conclusions

In this paper, the authors presented a thin-profile, resistive, film-based MTM–EM absorber exhibiting an operating frequency bandwidth of 20.8 GHz (123.1%), from 6.5 GHz to 27.3 GHz, with a 90% absorbance criterion. This includes parts of the C-band, X-band, Ku-band, and K-band. The highest absorbance of 99% occurs at 18.65 GHz. The proposed absorber was insensitive to the polarization and incidence angles in TE and TM mode at all operating frequencies, due to its highly symmetrical configuration. The working mechanism of the proposed work was analyzed and explained in detail by the surface current distribution and the surface power loss simulations. A prototype was built, and all the computed expectations were verified experimentally. The proposed MTM–EM absorber showed a wide-operating frequency range with a relatively thinner profile than in other works that use ITO films. It was also physically transparent since PET was used as a base film for the ITO coating. Once the supporter is flexible, it is believed that it could be effectively applied in curved glasses, such as a canopy or the flexible displays of mobile phones, as a means of reducing the RCS or absorbing unwanted EM energies.

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