Shielding Effectiveness Improvement of Non-Metallic Transparent Enclosures Using Gold Nano-Layer Deposition

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Abstract **─** In this paper we present the results of a simple optically transparent enclosure with efficient electromagnetic shielding. Firstly, Indium Tin Oxide (ITO) enclosures are designed for simultaneously providing high transmittance within a visible range and good shielding effectiveness (SE), where weight reduction, small size, and transparency are challenges. In the next step, gold Nano-layer films of various thicknesses are deposited on the patterned ITO glass using the thermal evaporation method. Then, by making a trade-off between optical transparency and SE, an optimized gold film thickness is selected. To assess the proposed approach, the final experimental results of copper, ITO, and gold deposited enclosures are compared. The results showed that a 9nm gold deposited ITO enclosure, provides efficient electromagnetic shielding better than the ITO enclosure (about 15 dB better at the resonance frequency and much closer to the copper enclosure) and at the same time, acceptable optical transparency.

Index Terms **─** Deposition, gold Nano-layer, shielding effectiveness, transparent enclosure.

I. INTRODUCTION

Today, the growth of wireless communications, such as satellites and Wi-Fi connections, electromagnetic shielding of high frequencies is needed. Electrical and electronic devices are commonly housed into metallic enclosures to reduce emissions or improve their immunity. From the viewpoint of electromagnetic compatibility due to the existence of slots and apertures for signal and power cable penetration and heat dissipation, the shielding efficiency of electromagnetic enclosures is degraded [1]. The ability of an electromagnetic enclosure to reduce the effect of undesired emission is represented by shielding effectiveness (SE). SE is defined as the ratio of field strength in the absence of an enclosure to the presence of an enclosure [2]. Metallic enclosures with apertures have been studied extensively in other previous work [3, 4]. Also, analytical models have been developed for a fast and accurate estimation of the metallic enclosures SE [5-7]. Nonetheless, a metallic enclosure cannot be considered as a good candidate for electromagnetic shielding, where weight, size reduction, and transparency are challenging.

Although meta-material slabs can provide good shielding with a reduced weight and size as well as can be tailored to obtain frequency selectivity [8], they are challenging especially when an optimum condition between optical transparency and SE is necessary.

Recent attempts to find transparent materials with high SE and good optical transparency have led to technological solutions [9] for applications such as displays of electronic devices, monitors, electrical panels, fashion electronic devices and integration with solar cells in Nano and cube satellites. Transparent enclosures can be realized on transparent conductive films, such as Indium tin oxide (ITO), fluorine-doped tin oxide, and silver-coated polymer film. Among the transparent conductors, ITO is more desirable as it offers a reasonable trade-off between optical transparency and minimum electrical resistivity [10-12]. However, the practical application of transparent ITO enclosures has been limited by their lower SE rather than metallic enclosures [13]. In recent years, a lot of effort has been

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made to fabricate transparent composite films with high SE. This has led to the usage of nanoparticle materials. For example graphene based composites have been used to obtain better SE for transparent conductive films [14-16]. The authors in [17] have attached a monolayer CVD graphene film on quartz substrate to a transparent ITO enclosure. Although, result of the proposed enclosure has demonstrated better electromagnetic shielding, this graphene loaded ITO enclosure has been considered entirely closed as there were no apertures in it. So, its practical application has been reduced dramatically.

In this paper, we provide a practical and simple solution to improve the SE of the transparent ITO enclosure with a circular aperture. In the first step, CST simulations are used to find the SE of ITO enclosures. Then, an optimum gold Nano-layer thickness is selected to make a trade-off between SE and the optical transparency of gold deposited ITO enclosure. Finally, in order to demonstrate the effectiveness of the method, performance results of copper, ITO glass, and gold Nano-layer deposited enclosures are compared.

This paper is organized as follows: In Section II, we discuss the characteristics of transparent conductors and the design and analysis of transparent enclosures is presented. In Section III, the fabrication of transparent ITO enclosure is described. Gold Nano-layer deposition using thermal evaporation technique is described in Section IV. Also, the selection of optimum gold Nano-layer thickness is presented in this section. Measurement results of copper, ITO and gold Nano-layer deposited enclosures are provided in Section V. The conclusion is given in Section VI.

II. TRANSPARENT ENCLOSURE

A. Transparent conductive films

In studies involving optically transparent conductive films, the performance of different materials has been assessed, among which, ITO is highly regarded. ITO is an n-type semiconductor with a wide energy gap (more than 3.5 eV) that offers a good trade-off between high optical transparency and minimum electrical resistivity in the visible light spectrum. An ITO film without layering on a substrate can be considered a good conductor to use in an enclosure, if its sheet resistance R_{sh} is low to restrict the ohmic losses and its thickness is high enough to limit skin depth losses. The optical transparency of the ITO film is estimated by using (1) [18]:

$$T \cong e^{-\frac{2T_c}{\delta}}, \tag{1}$$

where, T_c is the conductive film thickness and δ is the skin depth for visible wavelengths. According to [19], the sheet resistance of the ITO film can be obtained by using (2), where ρ is the resistivity of the ITO film:

$$R_{sh} = \frac{\rho}{T_c}. \tag{2}$$

One can see from (1), that a higher optical transparency needs thinner films while (2) shows that lower sheet resistance requires thicker films. In this paper, in order to determine the effects of gold deposition, we have used a 160nm thick ITO film with high optical transparency of about 89% and sheet resistance of 10 Ω⁄sq.

B. Transparent enclosure design

The Robinson et al. model is a simple analytical model based on transmission line theory that can be used for SE estimation of metallic enclosures with infinite conductivity. It has been developed for practical metallic enclosures with finite conductivity [20]. It still cannot analyse transparent enclosures accurately, due to its inability to take into account multi-layer panel effects. In this paper, we used three layer transparent panels including transparent dielectric (such as Glass, PET polymer sheet, and Plexiglas) and conductive transparent films (see Fig. 1). Hence, to analyse transparent enclosures, we have performed a 3D full wave electromagnetic analysis using the CST Microwave Studio based on the Finite Integration Technique and setting the proper characteristics of the materials constituting the enclosure.

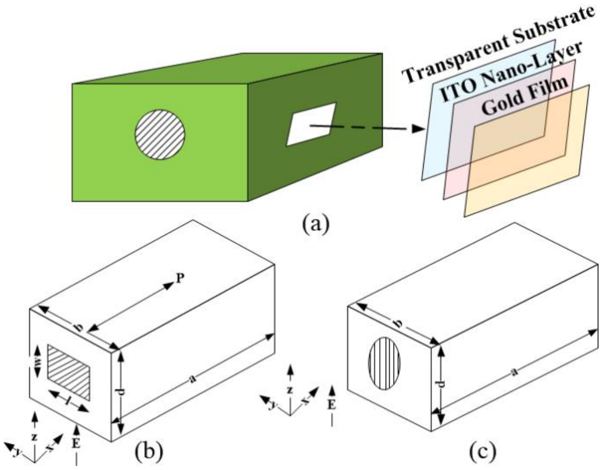


Fig. 1. Transparent enclosure: (a) panel configuration, (b) rectangular aperture, and (c) circular aperture.

SE is the most important factor in metallic enclosure performance while, optical transparency as well as the SE factor should also be considered in transparent enclosures. Therefore, by making a trade-off between these two factors, optimized ITO and glass thickness selection is necessary. So, based on CST optimization tools and Equations (1)–(2), we have selected optimum thicknesses of layers. As a result, we have selected

160nm thick ITO films that are mounted on a transparent dielectric substrate to make two-layer transparent panels. Such transparent enclosures with various dimensions, substrate thickness, and apertures (see Table 1) has been simulated and exposed to the normal incident of the plane wave. The electric field has been calculated in the center of enclosures. Also, for a better comparison between SE of transparent and metallic enclosures, copper enclosures with the same dimensions, apertures and thickness (equal to the substrate thickness) have been analysed, too.

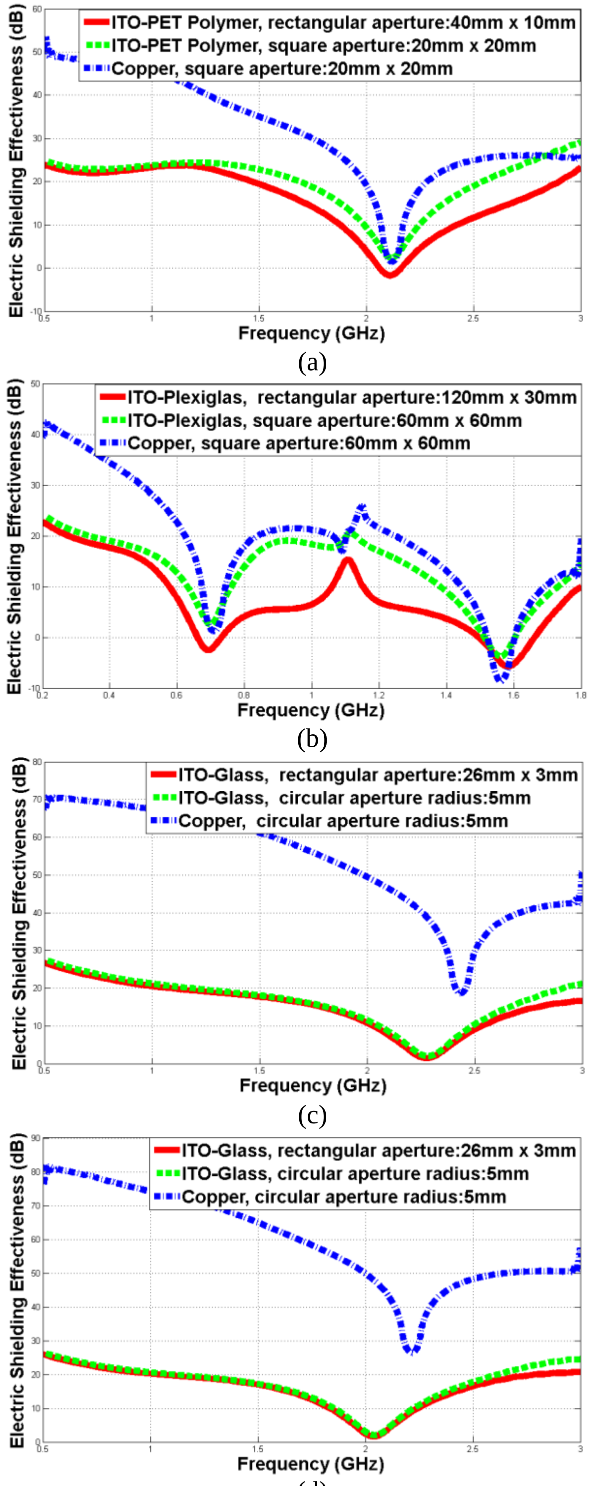
Table 1: Characteristics of ITO Enclosures

Sample	Substrate	Substrate Thickness	Enclosure Dimensions
1	PET Polymer	0.18mm	100mm × 100mm × 100mm
2	Plexiglas	1mm	300mm × 120mm × 300mm
3	Glass	1.5mm	90mm × 40mm × 90mm
4	Glass	2.2mm	100mm × 50mm × 100mm

SE results of ITO enclosures have been given in Fig. 2. One can see there is a significant difference between the SE of ITO and copper enclosures. Therefore, in practical applications, ITO enclosure shielding performance should be improved as will be discussed in the Section V.

III. ITO GLASS ENCLOSURE FABRICATION

Based on previous results, one can see that an ITO enclosure with square and circular aperture has better SE than one with a rectangular aperture (similar to a metallic one) [20, 21]. As observed in Fig. 2, as the thickness of enclosures is increased, the SE difference between transparent and metallic cases is higher. However, in practical application of transparent enclosure, the thickness should be lower than 2 mm, because of weight and size challenges. Hence, in order to consider the worst case, we have chosen 2.2 mm thick borosilicate glass as a substrate for transparent panels. Additionally, in order to simplify the manufacturing process (cutting and drilling); we have taken ITO enclosures with a circular aperture. Without any damages to the generality of the work, we have considered ITO enclosure dimensions of 100mm × 50mm × 100mm with a circular aperture radius of 5mm. 150nm thick ITO films have been deposited on the substrates using RF sputtering deposition technique.



(a)

(b)

(c)

(d)

Fig. 2. SE calculation of transparent enclosures with various panels and dimensions: (a) sample 1, (b) sample 2, (c) sample 3, and (d) sample 4.

In order to maintain conductivity at the edges of the enclosures, panels are connected by a silver paste internally and glue strips of copper externally (see sample A, Fig. 3).

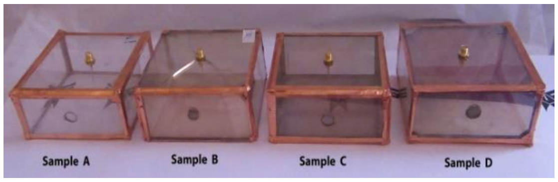


Fig. 3. Transparent enclosures have been fabricated using various transparent panels (see Table 2).

IV. GOLD NANO-LAYER DEPOSITED ITO ENCLOSURE

A. Gold Nano-layer deposition

As predicted in previous section, based on our measurement results (as observed in Fig. 4), the SE of ITO glass enclosure is very low compared to the metallic enclosure (with the same dimensions, aperture and the thickness equal to the substrate thickness).

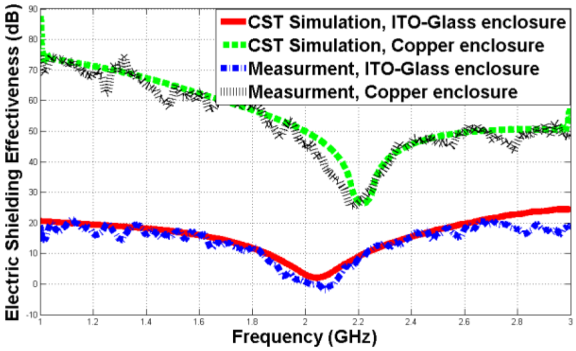


Fig. 4. SE Comparison of copper and ITO enclosures with the same dimensions, thickness and aperture.

To improve the SE, we used gold Nano-layers that homogenously deposited on the ITO glass panels, using thermal evaporation technique. We choose gold due to its good oxidation resistance, low penetration depth, and high electrical conductivity. This method is based on reducing the surface resistance of the panels to obtain a better conductor and therefore good SE. One technique is to use multilayer conductors. In such a case, several layers are placed in parallel, one on top of the other, and therefore the overall sheet resistance is decreased as observed in (3) [19]:

$$\frac{1}{R_{sh-Total}}=\frac{1}{R_{sh-ITO}}+\frac{1}{R_{sh-Gold}}, \tag{3}$$

where, R_{sh-ITO} and $R_{sh-Gold}$ are the sheet resistances of the ITO film and gold Nano-layer, respectively.

B. Thermal evaporation deposition technique

Thermal evaporation is utilized extensively to deposit Nano-layer films of materials on the substrates in semiconductor production. In this paper, gold Nano-layer films of various thicknesses have been deposited on the ITO glass panels by this technique. The process has been performed at an atmospheric pressure of 1e-5 and supply current of 100A. Before deposition, the panels were cleaned by rinsing them in a detergent solution and later in deionized water. They were finally dried with N_2 gas.

C. Selection the optimum thickness of gold film

Here we propose a practical approach to improve SE, based on gold Nano-layer deposition on the patterned ITO glass panels, the configuration of which has been shown in Fig. 1. The first step is to make a trade-off between SE and optical transparency, and the second step is the selection of the appropriate gold Nano-layer thickness. Therefore, gold Nano-layers of various thicknesses in the range of 3nm to 19nm have been deposited on the patterned ITO glass using the thermal evaporation technique.

Results from optical transparency measurements show that thicknesses higher than 13nm lead to very low transparency of about 50% (Fig. 5). On the other hand, based on the results of our simulation and also Equation (3), thicknesses lower than 3nm cannot improve SE, effectively.

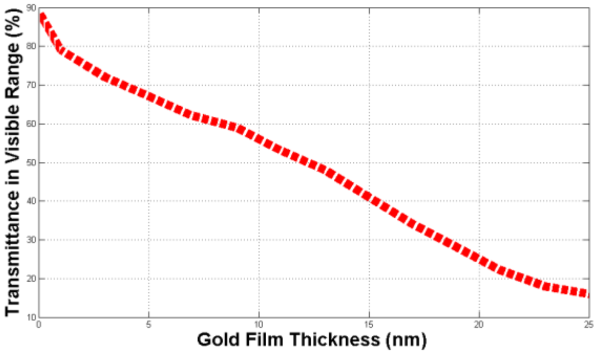


Fig. 5. Optical transparency results of gold deposited ITO glass panels at 550 nm wavelength, versus gold film thickness.

In the final step, 5nm, 7nm, and 9nm gold deposited panels were selected to fabricate transparent enclosures. As mentioned in Section IV, to connect the edges, gold deposited ITO glass panels were connected using silver glue internally and copper adhesive tape externally. Fabricated transparent enclosures can be seen in Fig. 3. Also, panels used in these enclosures have been described in Table 2.

Table 2: Transparent panel samples

Sample	Panel Layers	Layer Thicknesses
A	ITO-Glass	160nm - 2.2mm
B	Gold-ITO-Glass	5nm - 160nm - 2.2mm
C	Gold-ITO-Glass	7nm - 160nm - 2.2mm
D	Gold-ITO-Glass	9nm - 160nm - 2.2mm

V. RESULT AND DISCUSSION

A. Measurement

The SE of transparent enclosures was measured within a frequency range of 1 GHz to 3 GHz in an EMC chamber. A standard horn antenna was used to radiate electromagnetic waves, and an electric field measurement probe has been placed at the center of the enclosure (Fig. 6). The SE results of transparent enclosures have been shown in Fig. 7 (a).

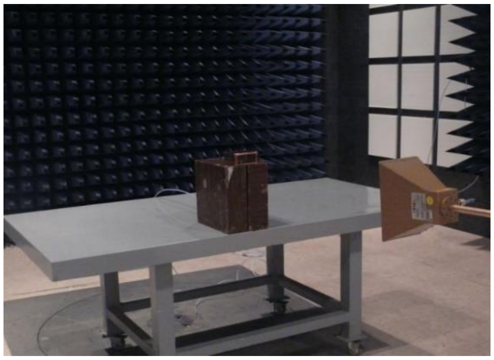
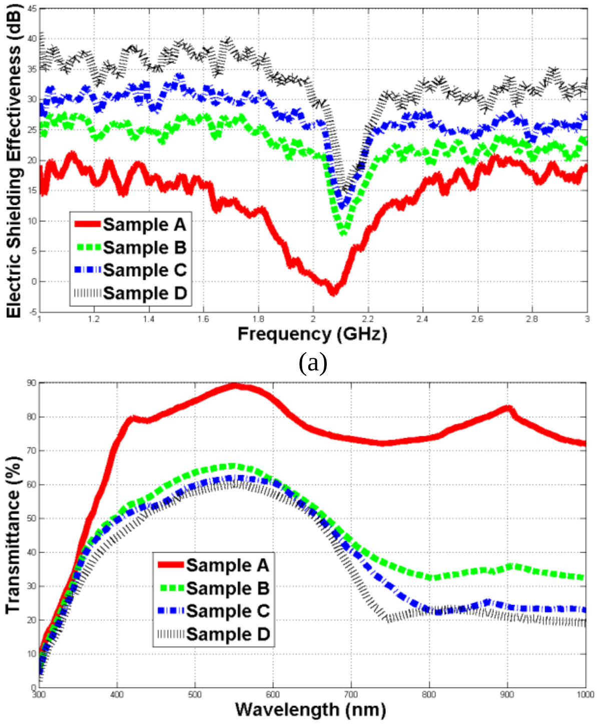


Fig. 6. SE measurement setup in EMC chamber.

Also, the optical properties of the composite panels are characterized by spectrophotometry.The transmittance spectra can be recorded within the 300nm–1000nm range by a spectrophotometer for normal incidence. The optical transparency measurements for the mentioned panels, shown in Fig. 7 (b), were conducted using a high resolution optical spectrometer in the optical laboratory.

B. Discussion

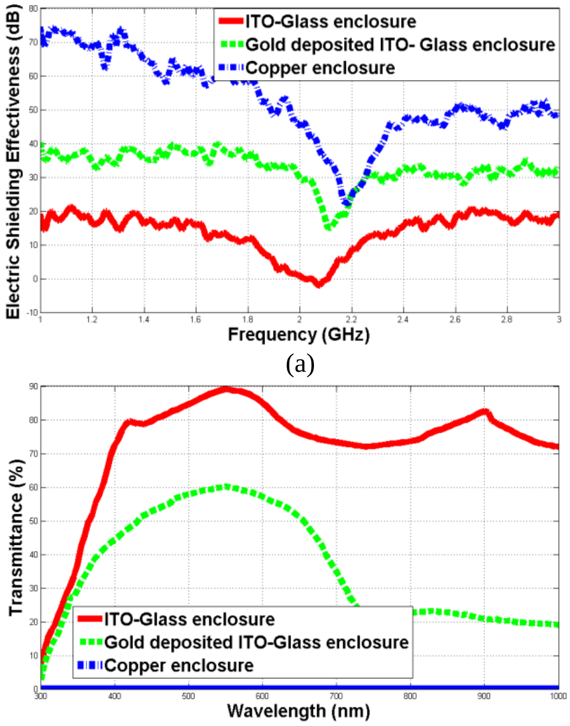
ITO glass enclosures can provide proper shielding and good transparency, simultaneously, but as discussed in the previous section its SE should still be improved to obtain SE closer to metallic enclosures. A homogenous deposition base on gold Nano-layer has been proposed in this paper.To assess the performance of the improvement method, a 2.2mm thick copper enclosure with the same dimensions and aperture (equal to the ITO enclosures) has been fabricated and measured too. The performance results of copper, ITO glass, and gold deposited ITO glass enclosures are compared in Fig. 8 (a) and Fig. 8 (b). As predicted by analysis results, measurement results show that, gold Nano-layer deposition increases the SE significantly and reduces optical transparency which verifies the theoretical relationships (1) to (3).



(a)

(b)

Fig. 7. Performance of transparent enclosures: (a) measured SE, and (b) measured optical transparency.



(a)

(b)

Fig. 8. Performance comparison between transparent and metallic enclosures: (a) SE and (b) optical transparency.

Therefore, optimized performance for transparent enclosures has been obtained by making a trade-off between SE and optical transparency factors. From the results, it can be inferred that while ITO glass enclosure does not have desirable SE, 9nm gold Nano-layer deposited ITO glass enclosure has more than 15 dB better SE at the resonance frequency (and much closer to the SE of metallic enclosure) as well as acceptable optical transparencies for practical applications (about 60% transmittance in 550nm wavelength), while a copper enclosure cannot provide any transmittance in the visible range. As shown in this paper, the proposed method has been used for 2.2mm enclosure (which is usually the worst case for transparent applications). This method improves the SE of ITO glass enclosures more efficiently (compared to the metallic enclosure performance), especially when the thickness of the enclosure walls is reduced.

VI. CONCLUSION

Metallic enclosures cannot be good candidates for electromagnetic shielding, where weight, size reduction, and transparency are challenging.

In this paper, we have proposed gold-ITO enclosures that can overcome mentioned challenges. Since an ITO enclosure cannot provide the desirable SE, in this paper we have proposed a practical solution to improve the performance of transparent enclosures. Gold Nano-layer films of various thicknesses were deposited on the patterned ITO glass panels to achieve better SE. Finally, by making a trade-off between SE and optical transparency, the optimum thickness of gold Nano-layer was selected. To assess the performance improvement method, copper, ITO, and gold deposited ITO enclosures have been compared.The results showed that a transparent enclosure with 9nm gold Nano-layer deposited ITO glass panels provides efficient SE and the same time acceptable transmittance within a visible range, while metallic enclosures cannot overcome transparency challenges. The proposed technique can improve the SE of ITO glass enclosures efficiently, especially when the thickness of the enclosure walls is reduced.

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