

AEROSPACE METAMATERIALS AND FUNCTIONAL COATINGS

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ABSTRACT

AEROSPACE METAMATERIALS AND FUNCTIONAL COATINGS

Ph.D. in Materials Science and Nanotechnology

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Optically transparent and electrically conductive thin-film coatings are widely used to functionalize surfaces of various high-technology platforms, including mobile phones, displays, detectors, and LEDs. Their integration into aviation transparencies, such as canopies, windshields, and windows, is widely known and used for de-icing purposes. However, there are limited reports or information available about using such thin-film coatings for electromagnetic interference (EMI) shielding, low observability (LO), and solar irradiation protection features. This thesis aims to study and demonstrate optically transparent aviation structures possessing the properties of EMI shielding, LO features, and solar radiation protection altogether. To this end, in this thesis, we specifically addressed the problem of achieving high EMI shielding and solar protection, which require high electrical conductivity, resulting in a trade-off reducing the optical quality and LO performance.

Transparent engineering polymers are widely used in structural parts in aviation thanks to their enhanced mechanical performance. However, good-quality films require high-temperature processes, which is not applicable to transparent aviation structures. Therefore, the architecture of layered films can be applied to meet the requirements of well-featured aviation transparencies. For these purposes, in the thesis we also designed monolithic and laminated aviation transparencies with surface modification based on stratified films and their patterned ones using numerical and experimental methods. We developed numerical approaches for the design of aircraft transparencies, including both the optical and electromagnetic requirements and validated our results.

We successfully conducted experimental studies for uniform large-area thin-film coatings onto aviation transparencies. The results revealed that EMI shielding and solar control performance were achieved with minimal optical losses for planar structures. LO requirement was incorporated into prototypes built on curved or laminated transparent structures instead of monolithic ones to sustain optical, solar protection, and EMI shielding performance to a possible extent. We showed that the low observability performance of such patterned structures, the metamaterials, is enhanced in terms of bandwidth and attenuation compared to the planar thin-film-coated monolithic counterparts. These multi-functional thin-film coatings are essential in aviation, especially for high-performance 5th-generation fighter jets and other civil applications.

This thesis paves the way for thin-film-coated transparent aviation structure designs across different domains, including visible, infrared, and microwaves, to enable their multi-functionality at large scales. The experimental large-area coating method guides the coating of a large and complex area to remove the limitation of metamaterial applications at the industrial level. We believe that our findings in this thesis will help to replace traditional planar thin film coatings with metamaterials at the industry scale, aiming to outperform traditional counterparts.

Keywords: Large-area thin-film coatings, metamaterials, electromagnetic interference shielding, low observability, solar radiation protection

ÖZET

HAVACILIK METAMALZEMELERİ VE FONKSİYONEL

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Optik geçirgen ve elektriksel iletken ince film kaplamalar, mobil telefonlar, ekranlar, dedektörler ve LED'ler gibi çeşitli yüksek teknoloji platformlarının yüzeylerini işlevselleştirmek için yaygın olarak kullanılmaktadır. Kaplamaların kanopiler, ön camlar ve pencereler gibi havacılık saydamlarına buz çözme amaçlı entegrasyonu yaygın olarak bilinmektedir. Ancak, bu tür ince film kaplamaların elektromanyetik girişim (EMG) kalkanlama, düşük görünürlük (DG) ve solar koruma özellikleri hakkında sınırlı rapor veya bilgi bulunmaktadır. Bu tezin amacı, EMG kalkanlama, DG ve solar radyasyon koruma özelliklerini bir arada bulunduran optik olarak saydam havacılık yapılarını incelemek ve gösterimini yapmaktır. Bu amaçla, bu tezde, yüksek elektriksel iletkenlik gerektiren ve bunun sonucunda optik ve DG performansını azaltan yüksek EMG kalkanlama ve solar koruma elde etme problemine odaklanılmıştır.

Saydam mühendislik polimerleri, gelişmiş mekanik performansları sayesinde havacılıkta yapısal parçalarda yaygın olarak kullanılmaktadır. Ancak, kaliteli filmler yüksek sıcaklık gerektiren işlemler gerektirirken, bu durum saydam havacılık yapıları için uygulanabilir değildir. Bu nedenle, katmanlı film mimarisi, gelişmiş havacılık saydamlarının gereksinimlerini karşılamak için uygulanabilir. Bu amaçlar doğrultusunda tezde, sayısal ve deneysel yöntemler kullanarak tabakalı filmler ve bunların desenli versiyonları esas alınarak yüzeyi modifiye edilmiş monolitik ve lamine havacılık saydamları tasarlanmıştır. Havacılık saydamlarının tasarımı için hem optik hem de elektromanyetik gereksinimleri içeren sayısal yaklaşımlar geliştirilmiş ve doğrulanmıştır.

Havacılık saydamları üzerinde geniş alanda homojen ince film kaplamaları için deneysel çalışmalar başarıyla gerçekleştirilmiştir. Sonuçlar, düzlemsel yapılarda minimum optik kayıplarla EMG kalkanlama ve solar koruma performansının elde edildiğini ortaya koymuştur. Optik, solar koruma ve EMG kalkanlama performansını mümkün olduğunca iyileştirmek amacıyla monolitik yapılar yerine kavisli veya lamine saydam yapılar üzerine uygulanan prototiplerde DG gereksinimi incelenmiştir. Düzlemsel filmlerin yüzeyi desenlenerek oluşturulan metamateryallerin, monolitik yapılarla karşılaştırıldığında bant genişliği ve sönümlenme açısından DG performansını artırdığı gösterilmiştir. Bu çok işlevli ince film kaplamalar havacılıkta, özellikle yüksek performanslı 5. nesil savaş uçakları ve diğer sivil uygulamalarda vazgeçilmezdir.

Bu tez, görünür, kızılötesi ve mikrodalgalar da dahil olmak üzere farklı alanlarda ince film kaplı havacılık saydamlarının çok işlevli kullanımını büyük ölçeklerde mümkün kılacak tasarımların önünü açmaktadır. Deneysel geniş alan kaplama yöntemi, endüstriyel düzeyde metamateryale uygulamalarının sınırlamalarını ortadan kaldırmak için geniş ve karmaşık bir alanın kaplanmasına rehberlik etmektedir. Bu tezdeki bulguların, geleneksel düzlemsel ince film kaplamaların yerine endüstriyel ölçekte metamateryallerin kullanılmasına katkı sağlayarak, geleneksel muadillerinden daha yüksek performans sağlayacağına inanılmaktadır.

Anahtar sözcükler: Geniş alan ince film kaplamalar, metamateryaller, elektromanyetik girişim kalkanlama, düşük görünürlük, solar kalkanlama

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Contents

CHAPTER 1.....	1
Introduction.....	1
1.1. Motivation.....	2
1.2. Organization of the Thesis	3
CHAPTER 2.....	5
Scientific Background.....	5
2.1. Optically Transparent Electromagnetic Interference Shields.....	6
2.2. Low Observability & Stealth Technology	9
CHAPTER 3.....	12
Numerical Modeling of Aviation Transparencies for Electromagnetic Interference	
Shielding and Low Observability	12
3.1. Monolayer and Laminated Structures	16
3.2. Patterned Structures – Metasurfaces	30
CHAPTER 4.....	36
Optically Transparent Electromagnetic Interference Shielding of ZTO/Ag/ZTO	36
4.1. Fabrication and Characterization	37
4.2. Electromagnetic Interference Shielding Performance.....	41
4.3. Optical Performance	45
4.4. Structural Characterization	65
4.5. Summary	70
CHAPTER 5.....	71
Three-Dimensional Optical Performance Analysis of Aviation Transparencies.....	71
5.1. Angular Deviation Analysis.....	75

5.2. Optical Transmittance Analysis	79
5.3. Summary	84
CHAPTER 6.....	85
Conclusion	85
6.1. Contributions to Scientific Knowledge and Industry	85
6.2. Challenges and Future Outlook	87
6.3. Publications and Patents	89
Bibliography	91



List of Figures

Figure 2.1. Schematic of EMI shielding material with EM-wave interactions including transmitted (red), reflected (blue), and absorbed (green) EM waves.	7
Figure 2.2. Conventional radar absorbers: (a) Salisbury screen composed of resistive sheet, low loss layer and metal plate, (b) Jaumann absorber composed of resistive layers and low loss layers with a metal plate, and (c) Dallenbach layer composed of loss layer with a metal plate.	10
Figure 3.1. Free-space measurement system, which utilizes a network analyzer connected to Port – 1 and Port – 2, shown along with the S -parameters (i.e., S_{11} , S_{22} , S_{21} , S_{12}). The material under test is placed between the ports.	14
Figure 3.2. (a) CST Microwave Studio 3D schematics of the unit-cell setup used in our numerical calculations. The setup includes material under test placed between <i>Port – 1</i> and <i>Port – 2</i> . (b) Complex permittivity ($\varepsilon = \varepsilon' - j\varepsilon''$) of PC in the frequency range of 2–20 GHz extracted from S -parameters.	15
Figure 3.3. Relationship between the scattering parameters (S -parameters) and the fraction of power.	17
Figure 3.4. Numerically calculated spectral transmission loss (dB) of conductive films with sheet resistance values of 10 $\Omega/\square$, 15 $\Omega/\square$, 20 $\Omega/\square$, 25 $\Omega/\square$, 30 $\Omega/\square$, 35 $\Omega/\square$, 40 $\Omega/\square$, 45 $\Omega/\square$, 50 $\Omega/\square$, 100 $\Omega/\square$, and 150 $\Omega/\square$ across 1–20 GHz.	18
Figure 3.5. Numerically calculated spectral transmission loss (dB) of uncoated PC monolayers with varying thickness values between 1–12 mm across 1–20 GHz.	19
Figure 3.6. Numerically calculated spectral transmission loss (dB) of the conductive layer with a sheet resistance value of 10 $\Omega/\square$, applied to the PC substrate with varying thickness values between 1–12 mm across 1–20 GHz.	20
Figure 3.7. Numerically calculated spectral reflection loss (dB) of the conductive layer with a sheet resistance value of 10 $\Omega/\square$, applied to the PC substrate with varying thickness values between 1–12 mm across 1–20 GHz.	21
Figure 3.8. Schematic of the structure to be optimized based on the Salisbury Screen. The structure composed of resistive and conductive layers (shown in green) applied to the top and bottom of the PC monolayer (shown in blue).	21
Figure 3.9. Numerically calculated reflection loss (dB) and transmission loss (dB) of the optimized structures 4.40 mm PC + 10 $\Omega/\square$ and 413 $\Omega/\square$ + 4.40 mm PC + 10 $\Omega/\square$ across 1–20 GHz.	23
Figure 3.10. Numerically calculated transmittance, reflectance and absorbance of the optimized structures 4.40 mm PC + 10 $\Omega/\square$ and 413 $\Omega/\square$ + 4.40 mm PC + 10 $\Omega/\square$ across 1–20 GHz.	23

Figure 3.11. Numerically calculated spectral reflection loss (dB) of the optimized structure ($413 \Omega/\square + 4.40$ mm PC + $10 \Omega/\square$) in 1–20 GHz at different angles of incidence ($0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ$) for the vertical (V-pol) and horizontal (H-pol) polarizations.	25
Figure 3.12. Numerically calculated spectral transmission loss (dB) of the optimized structure ($413 \Omega/\square + 4.40$ mm PC + $10 \Omega/\square$) in 1–20 GHz at different angles of incidence ($0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ$) for the vertical (V-pol) and horizontal (H-pol) polarizations.	26
Figure 3.13. Schematic of the structure to be optimized based on Jaumann design principle. The structure is composed of resistive layers (shown in green) applied to the top and bottom of the PC substrate (shown in blue).	27
Figure 3.14. Numerically calculated spectral reflection loss (dB) of the laminated structure (4.40 mm PC + $150 \Omega/\square + 4.40$ mm PC + $10 \Omega/\square$) in 1–20 GHz at different angles of incidence ($0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ$) for the vertical (V-pol) and horizontal (H-pol) polarizations.	28
Figure 3.15. Numerically calculated spectral transmission loss (dB) of the laminated structure (4.40 mm PC + $150 \Omega/\square + 4.40$ mm PC + $10 \Omega/\square$) in 1–20 GHz at different angles of incidence ($0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ$) for the vertical (V-pol) and horizontal (H-pol) polarizations.	29
Figure 3.16. (a) Side-view of the structure, (b) geometrical parameters (a, b, c, d, e) of the single-square pattern to be optimized, (c) the top view and (d) the bottom view of the unit cell, and (e) the perspective view of the structure.	31
Figure 3.17. Numerically calculated spectral reflection loss (dB) of the patterned structure ($16 \Omega/\square$ patterned layer + 4.40 mm PC + $10 \Omega/\square$ planar layer) in 1–20 GHz at different angles of incidence ($0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ$) for the vertical (V-pol) and the horizontal (H-pol) polarizations.	32
Figure 3.18. Numerically calculated spectral transmission loss (dB) of the patterned structure ($16 \Omega/\square$ patterned layer + 4.40 mm PC + $10 \Omega/\square$ planar layer) in 1–20 GHz at different angles of incidence ($0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ$) for the vertical (V-pol) and horizontal (H-pol) polarizations.	33
Figure 3.19. Numerically calculated absorption of the PC, PC + $10 \Omega/\square$, $413 \Omega/\square +$ PC + $10 \Omega/\square$, $16 \Omega/\square +$ PC, and $16 \Omega/\square +$ PC + $10 \Omega/\square$ in the frequency range of 1–20 GHz at normal angle ($\theta = 0^\circ$). The thickness of the monolayer PC is 4.40 mm for all structures.	34
Figure 4.1. Schematic of the 2-inch scanning magnetron gun connected to a vacuum-compatible three-axis stepper motor, used for achieving uniform coating over large areas.	38
Figure 4.2. (a) Refractive index n and (b) extinction coefficient k of PC substrate, ZTO film, and Ag film in 400–1000 nm.	40

Figure 4.3. Sheet resistance measurements from different zones of ZAZ-PC along with (b) zone number mapping on the 50 cm × 50 cm surface.	41
Figure 4.4. (a) Free-space system used for experimental measurements, including a network analyzer connected to Port – 1 and Port – 2 and lenses to focus electromagnetic waves. The ZAZ-PC under test is placed between the ports. (b) Schematic of the unit cell module, (c) sheet resistance dependent transmission loss (dB) and transmission (T%), and (d) experimentally measured and numerically computed transmission loss and shielding effectiveness of the ZAZ stratified structure on 5.8 mm thick PC over 50 cm × 50 cm area.	43
Figure 4.5. Numerically calculated electric field intensity mapping of (a) the PC alone and (b) the ZAZ-PC structures at 10 GHz.	44
Figure 4.6. Numerically calculated transmission (T%), reflection (R%) and absorption (A%) of PC and ZAZ-PC structures across 2 - 20 GHz.	44
Figure 4.7. (a) Schematic illustration of interactions between multilayers; Incident (I) = Reflected (R) + Transmitted (T) + Absorbed (A). $T=T_1+T_2+T_3+T_4$ and $R=R_1+R_2+R_3+R_4$. (b) The schematic diagram depicts the structure used in the analytical calculations, consisting of a sandwiched film on a 5.8 mm PC substrate. In the sandwiched film, the Ag layer thickness was fixed to 18 nm, and <i>top ZTO</i> and <i>bottom ZTO</i> layers were swept between 0 and 60 nm.	46
Figure 4.8. (a) Calculated average transmission T_{mean} in 400–700 nm, (b) calculated average reflection R_{mean} in 400–700 nm, and (c) calculated average absorption for the PC – ZTO <i>bottom</i> /Ag (18 nm)/ZTO <i>top</i> structure on 5.8 mm thick PC while varying film thicknesses of the <i>top</i> and <i>bottom</i> ZTO layers.	47
Figure 4.9. (a) Calculated average transmission T_{mean} in 400–700 nm, (b) calculated average reflection R_{mean} in 400–700 nm, and (c) calculated average absorption in 400–700 nm for the PC – ITO <i>bottom</i> /Ag (18 nm)/ ITO <i>top</i> structure on 5.8 mm thick PC while varying film thicknesses of the top and bottom ITO layers.	49
Figure 4.10. (a) Calculated average transmission T_{mean} in 400–700 nm, (b) calculated average reflection R_{mean} in 400–700 nm, and (c) calculated average absorption A_{mean} in 400–700 nm for the PC – ZTO <i>bottom</i> /Ag /ZTO <i>top</i> structure on 5.8 mm thick PC. The top and bottom ZTO layers are identical.	50
Figure 4.11. (a) Calculated average transmission T_{mean} in 700–1000 nm, (b) calculated average reflection R_{mean} in 700–1000 nm, and (c) calculated average absorption A_{mean} in 700–1000 nm for the PC – ZTO <i>bottom</i> /Ag /ZTO <i>top</i> structure on 5.8 mm thick PC. The top and bottom ZTO layers are identical.	51
Figure 4.12. Spectral transmission of the ZAZ-PC structure with and without a coating in the (a) visible (400–700 nm) and (b) near-infrared (700–1000 nm) regions.	52

Figure 4.13. Schematic of the ZTO <i>bottom</i> (20 nm)/Ag (18 nm)/ZTO <i>top</i> 40 (nm) coated PC (a), and calculated spectral transmission in 400–700 nm for various PC thickness values of 1.0 mm, 5.8 mm, 10.0 mm, 15.0 mm, and 20.0 mm.	53
Figure 4.14. Schematic of the ZTO <i>bottom</i> (20 nm)/Ag (18 nm) (a) and Ag (18 nm)/ZTO <i>top</i> (40 nm) (b) coatings on 5.8 mm PC and (c) the calculated spectral transmission in 400–700 nm for Ag, ZTO <i>top</i> , ZTO <i>bottom</i> and ZAZ coatings.	54
Figure 4.15. Calculated average transmission (a), reflection (b), and absorption (c) of the ZTO <i>top</i> /Ag (18 nm)/ZTO <i>bottom</i> structure on the 5.8 mm thick PC in the near-infrared for night-vision applications.	55
Figure 4.16. Spectral solar irradiance in the wavelength range of 280–4000 nm according to the ASTM G173–03.	57
Figure 4.17. (a) Transmittance spectra and (b) transmitted solar irradiance as a function of the wavelength (780–2000 nm) for the PC and ZAZ-PC coatings. The top panel presents transmission percentage, while the bottom one shows transmitted solar irradiance in W/m ²	59
Figure 4.18. (a) Reflection spectra and (b) reflected solar irradiance as a function of the wavelength (780–2000 nm) for the PC and ZAZ-PC coatings. The top panel presents reflection percentage, while the bottom one shows reflected solar irradiance in W/m ²	60
Figure 4.19. (a) Spectral absorbance and (b) solar irradiance absorbed through the PC, ZAZ-PC, and PC-ZAZ as a function of the wavelength (780–2000 nm). The top panel presents absorption percentage, while the bottom one shows reflected solar irradiance in W/m ²	61
Figure 4.20. Illustration of the PC's response to solar irradiance (SI), both with and without the ZAZ coatings in the 780–2000 nm wavelength range. (a) PC without coating exhibits transmittance of 315.81 W/m ² , reflecting 33.62 W/m ² of solar irradiation. (b) PC with an exterior ZAZ coating significantly increases SI reflectance to 223.11 W/m ² and reduces transmitted SI to 135.22 W/m ² . (c) PC with an interior ZAZ coating achieves the same SI transmittance value of 135.22 W/m ² and reflects 157.57 W/m ² of the SI.	62
Figure 4.21. (a) Cross-sectional FIB image along with HRTEM inset and (b) SIMS analysis of the ZAZ–PC structure.	66
Figure 4.22. Representative (a) AFM 3D and (b) 2D topography images of the 5.8 mm thick PC substrate without thin-film coatings.	67
Figure 4.23. Representative AFM 2D and 3D topography images of different regions of the ZAZ–PC structure with RMS surface roughness values of (a) 1.79 nm, (b) 2.23 nm, (c) 1.38 nm, and (d) 1.48 nm.	67
Figure 4.24. Surface roughness of the PC-ZAZ from an area of 140 μm x 1000 μm according to the JIS B0601:2001 standard.	68

Figure 4.25. GIXRD result of the ZAZ film on PC substrate.	69
Figure 4.26. Photo image of a 50 cm × 50 cm optically transparent EMI shielding of PC-ZAZ.	69
Figure 5.1. Representative model of the canopy with a ray source (shown in red dot) positioned at the design eye point. We use the control screen to determine the coordinates of the rays.	74
Figure 5.2. Solid model of the (a) the 3D canopy transparency and (b) its meshed version. (c) Side-view of the canopy transparency with a ray source shown in red, positioned at the design eye point. (d) 2D architecture of a thin-film-coated canopy made of optically transparent polymers such as PMMA or PC. The thin-film coating consists of ZTO Top /Ag/ZTO Bottom.	75
Figure 5.3. Angular deviation (in radians) mapping of the (a) 10 mm, (b) 20 mm and (c) 30 mm uncoated PC at the wavelength of 550 nm with perspective view.	77
Figure 5.4. Angular deviation (in Rad) mapping of the (a) 10, (b) 20 and (c) 30 mm uncoated PMMA at the wavelength of 550 nm with perspective view.	78
Figure 5.5. Optical transmittance mapping of the 10 mm (a), 20 mm (b) and 30 mm (c) PC at the wavelength of 550 nm with perspective.	80
Figure 5.6. Optical transmittance mapping of the 10 mm (a), 20 mm (b) and 30 mm (c) PMMA at the wavelength of 550 nm with perspective.	81
Figure 5.7. Numerically calculated optical transmittance at 550 nm for ZAZ-coated PC with a thickness of (a) 10 mm, (b) 20 mm, and (c) 30 mm.	83
Figure 5.8. Numerically calculated optical transmittance at 550 nm for ZAZ-coated PMMA with a thickness of (a) 10 mm, (b) 20 mm, and (c) 30 mm.	83

List of Tables

Table 3.1. Average transmission (T%), reflection (R%), and absorption (A%) of the optimized structure ($413 \Omega/\square$ + 4.40 mm PC + $10 \Omega/\square$) in 1–20 GHz at different angles of incidence (0° , 15° , 30° , 45° , 60°) for the H- and V-polarizations.	25
Table 3.2. Average transmission (T%), reflection (R%), and absorption (A%) of the laminated structure (4.40 mm PC + $150 \Omega/\square$ + 4.40 mm PC + $10 \Omega/\square$) in 1–20 GHz at different angles of incidence (0° , 15° , 30° , 45° , 60°) for the H- and V-polarizations.....	29
Table 3.3. Average transmission (T%), reflection (R%), and absorption (A%) of the laminated structure ($16 \Omega/\square$ patterned layer + 4.40 mm PC + $10 \Omega/\square$ planar layer) in 1–20 GHz at different angles of incidence (0° , 15° , 30° , 45° , 60°) for the H- and V-polarizations.	34
Table 4.1. Average analytical and experimental transmission (T%) of the bare PC and ZAZ–PC in the visible (400–700 nm) and the near-infrared (700–1000 nm) regions.....	53
Table 4.2. Average fraction of power transmitted, reflected, and absorbed through the structures of uncoated-PC, PC-ZAZ (coating at the interior side), and ZAZ-PC (coating at the exterior side) in the wavelength range of 780–2000 nm.	61
Table 4.3. Summary of total solar irradiance transmitted, reflected, and absorbed through the structures of uncoated-PC, PC-ZAZ (coating at the interior side), and ZAZ-PC (coating at the exterior side) in the wavelength range of 780–2000 nm.	62
Table 5.1. Refractive indices (n) and extinction coefficients (k) of PMMA, PC, ZTO and Ag at the wavelengths (λ) of 550 nm and 700 nm.	74
Table 5.2. Minimum and maximum values of angular deviation (in mRad) of 10, 20, and 30 mm PC at the wavelength (λ) of 550 and 700 nm.	78
Table 5.3. Minimum and maximum values of angular deviation (in mRad) of 10, 20, and 30 mm PMMA at the wavelength (λ) 550 and 700 nm.	78
Table 5.4. Minimum and maximum values of optical transmittance of 10 mm, 20 mm, and 30 mm uncoated PMMA and uncoated PC at the wavelength (λ) of 550 nm.	80
Table 5.5. Minimum and maximum values of numerically calculated optical transmittance of ZAZ–PC at the wavelength (λ) of 550 nm with thicknesses of 10 mm, 20 mm, and 30 mm.	82

Chapter 1

Introduction

Electromagnetic interference (EMI) shielding and low observability (LO) technologies trace back to World War II when radar systems and electronic countermeasures took on strategic importance [1]–[3]. In the earlier stages of these technologies, traditional solutions consisted of thick and heavy metals, incorporated into structures that were not optically transparent [4]. The advancement in the conductive oxides and thin metallic films comes with optical transparency and electrical conductivity [5]. These innovations laid the foundation of optoelectronics for today's diverse range of optically transparent thin-film coatings.

As electromagnetic pollution increases in our daily lives due to the increased use of electronic devices, protecting systems from external sources is essential [6], [7]. Optically transparent EMI shields have been used in architectural glazing [8], aircraft windscreens [9], and consumer electronics [10], where visibility is paramount. Architects and engineers specify transparent EMI-blocking windows in critical facilities including data centers, hospitals, and labs. In parallel to the

EMI shielding, the LO feature has expanded, especially in military platforms, with the advancement in the sensors and radar systems [11], [12].

More recently, multi-functional usage of opaque and optically transparent thin-film coatings in civil and military domains has gained significant attention [13], [14]. One example is that transparent structures use thin-film coatings to control cabin temperatures, easing dependence on air-conditioning and boosting fuel efficiency in automotive and aviation [15], [16]. Despite notable progress in the thin-film coating technology, scaling up transparent thin-film coatings for multi-functional purposes such as EMI shielding, stealth, and solar control continues to pose challenges in the industry. The trade-off between high optical and electromagnetic performance requires careful balancing of film thickness over uniformity, especially for free-form objects. Fine-tuning film thickness through deposition parameters is crucial to achieving a high optoelectrical performance balance.

This thesis extends the present knowledge of EMI shielding and LO features, considering the trade-off with optical performance. Our approach covers thin-film architectural design in different domains and large-scale fabrication, establishing a ground for the next generation of aerospace innovations and beyond. Furthermore, we believe these findings will help the civil and military use of transparent conductive materials for large-scale applications and enhance aircraft stealth capabilities, pilot/passenger comfort, and operational efficiency.

1.1. Motivation

The objective of this thesis is to advance the large-area application of thin-film coatings for electromagnetic and optical features for multi-purposes. These multi-purposes include the EMI shielding and LO of the transparent structures. One motivation in this thesis work is filling the gap in the literature for possible use of large-area thin films in stealth technologies and aviation security-related

applications. In addition, we combine these electromagnetic features with the optical transparency, night-vision, and solar radiation protection to provide multifunctionality. To this end, we used numerical methods to design thin-film coated transparent structures utilized with the electromagnetic interference shielding and low observability features as well as optical transparency and solar radiation protection.

The thesis describes implementing low-observable characteristics and EMI shielding onto the two- and three-dimensional aviation transparencies while maintaining high optical transparency and solar protection. This thesis investigates the capability of these materials and geometries for furthering aviation transparency technologies to provide stealth capability with EMI shielding without sacrificing optical transparency. This thesis work will guide the realization of optically transparent and opaque metamaterials, which primarily require large-area coating, for next-generation applications while meeting contradictory optoelectrical requirements that are not possible with traditional structures.

1.2. Organization of the Thesis

In the subsequent chapter, we present the scientific background of electromagnetic interference shielding and low-observability technologies within optically transparent and electrically conductive planar coatings and their patterned versions, widely known as metamaterials.

In Chapter 3, we explain key mechanisms including optical reflection, absorption, and transmission, providing a basis for understanding EMI shielding and LO features. We used numerical techniques to explain the electromagnetic

characteristics of mono- and multi-layer structures with planar and patterned thin-film coatings.

In Chapter 4, we present our findings from our publication [17] on the large-area optically transparent EMI shield. In this study, we applied a sandwiched thin-film coating to a transparent structure, utilizing a large-scale robotic magnetron sputtering system, and engineered its optical and electrical properties. Here we examine the interaction of thin-film coatings with the electromagnetic waves for EMI shielding for planar structures. We also discuss its application for LO features using the numerical methods discussed in Chapter 3. In addition to EMI shielding and LO features, Chapter 4 covers the optical response related to optical clarity, night-vision and solar protection performances.

In Chapter 5, we present our ray tracing methodology for three-dimensional aviation transparencies. Here we address the optical performance criteria of transparent structures used in aviation regarding optical clarity and distortion.

In Chapter 6, we summarize the contributions of our thesis research work to both the academic understanding of EMI shielding and LO in optically transparent structures and their potential applications within the industry. Our research work in this thesis includes the large-area fabrication, characterization, and engineering of planar coatings and metamaterials. This thesis uncovers and addresses the obstacles in large-scale optically transparent thin films and their applications for EMI shielding and LO features, night-vision applications, and thermal management.

Chapter 2

Scientific Background

This thesis work includes designing optically transparent, electrically conductive thin-film coatings and large-scale fabrication. Before presenting the details of our work, we find it helpful to provide an overview of electromagnetic interference (EMI) shielding and low observability (LO) technologies and their challenges when integrated with optically transparent aviation structures based on our work [17].

In Section 2.1, we provide an overview of EMI shielding and their design constraint for optically transparent EMI shields. In Section 2.2, we describe low observability, also known as stealth technology and design methodologies of optically transparent structures for stealth applications.

2.1. Optically Transparent Electromagnetic Interference Shields

The ability to shield EMI is of critical importance in electronics [18], aviation and aerospace [19]–[24], automotive [25]–[28], medical and healthcare [29]–[31], and telecommunications [32]–[34]. For example, EMI can cause signal degradation, noise, data corruption, and even system failure, jeopardizing the safety and efficiency of aircraft operations [35]. Therefore, it is essential to shield the effects of EMI and protect electronic components from malfunctioning or failure.

EMI shields are widely used particularly in aerospace applications to protect electronic systems such as radars, communications, monitoring, and avionics from EMI [36]. However, most conventional EMI shielding materials are opaque to visible light [37]. EMI shielding with high optical transmission and low electrical resistivity has been challenging, in particular over large areas. Thin films with a high level of electrical conductivity require high-temperature processes, which cannot be applied to heat-intolerant substrates such as polycarbonate (PC) [38]. One of the most effective approaches for achieving improved optical transmission and electrical conductivity relies on sandwiched films using transparent conductive oxides (TCOs) with noble metals (i.e., TCO/metal/TCO) [39].

The metal film's thickness is the primary factor affecting the electrical conductivity of TCO/metal/TCO structures. The electrical conductivity decreases substantially below a critical value that ranges between 5 – 15 nm [40]–[46] due to the discontinuities in such thin films. Besides electrical properties, significant disparities may exist between optical constants of the bulk and thin film of the same material that stems from microstructural variations [47]–[49].

A schematic of the EMI shield is shown in Figure 2.1, including the EM wave-matter interactions including transmission, reflection, and absorption along with the skin depth (δ). The skin depth is proportionally related to the frequency (f), electrical conductivity (σ), and magnetic permeability (μ) using the following relation:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (2.1)$$

The skin depth of non-magnetic metals ($\mu=1$) in the visible region is a few to a few tens of nanometers depending on the electrical conductivity and frequency [50], [51]. The thickness of the layer should be limited to the skin depth since, above this limit, most of the visible light is exponentially attenuated at the visible frequencies. As the thickness of the metal or TCO increases, the electrical conductivity is enhanced while the optical transparency decreases. Hence, it is crucial to design structures with a thickness smaller than the skin depth in the visible region while being large enough to reflect RF waves while designing optically transparent EMI shields.

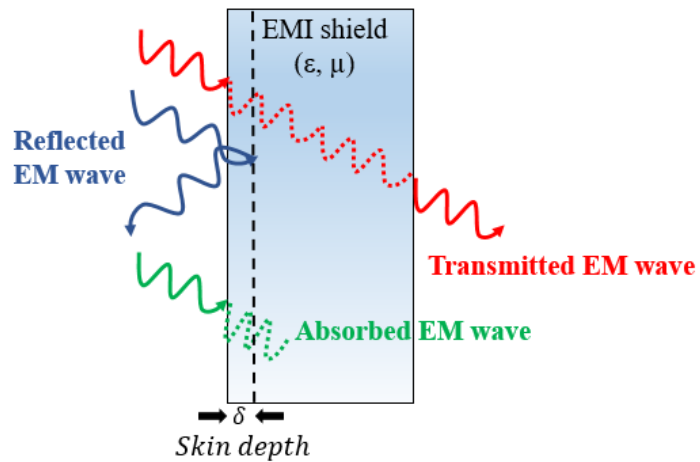


Figure 2.1. Schematic of EMI shielding material with EM-wave interactions including transmitted (red), reflected (blue), and absorbed (green) EM waves.

Numerous studies have previously been conducted on optically transparent and electrically conductive TCO/metal/TCO structures. Some of the most commonly employed TCOs in these structures include indium tin oxide (ITO), zinc tin oxide (ZTO), zinc oxide (ZnO), Al-doped zinc oxide (AZO), and molybdenum trioxide (MoO_3), often in combination with metals such as gold (Au), silver (Ag), aluminum (Al), and copper (Cu) as the intermediate layers [52]–[57]. However, using these materials in TCO/metal/TCO structures has limitations. The high cost of Au, the diffusion problem of Cu between layers [58], the brittleness and scarcity of indium [59], [60], the toxicity of MoO_3 [61], and the sensitivity of AZO to moisture [62] have all restricted their applicability. To address these issues, it is possible to use Ag as the metal layer and ZTO as the TCO because of their relatively low optical absorption, cost-effectiveness, and environmental friendliness [63], [64].

Several previous studies have investigated the optical and electrical properties of ZTO/Ag/ZTO (ZAZ) multilayer films on glass and polymer substrates. However, the largest substrates utilized were limited to laboratory scales, enabled by roll-to-roll sputtering, which is not applicable to large-scale, rigid, free-form objects [65]–[70]. For the aforementioned reasons, we studied the ZAZ thin-film coatings utilized for EMI shielding in a broad frequency range at a large scale, which needs a continuous and uniform coating network over a large area. We systematically studied EMI shielding properties using the measured dielectric constants in Chapter 3 and the optical performance using the measured thin-film optical constants in Chapter 4, respectively.

2.2. Low Observability & Stealth Technology

It is useful to explain the low observability (LO) for the thesis work addressing the problem of LO and here we discuss how optically transparent EMI shields (discussed in Section 2.1) can be utilized for LO applications. The EMI shielding technology focuses on blocking electromagnetic waves from passing through a structure and preventing interference. In contrast, the LO technology utilizes stealth technology to either absorb or redirect electromagnetic waves into undetectable directions, providing low visibility to radars and sensors.

LO technology has become vital, especially for military aircraft that aims to reduce detection by radar and sensor systems, thereby reducing radar cross-section (RCS). One way to reduce RCS is to use radar-absorbing structures (RASs) that make air platforms less visible to radar systems. RASs are engineered to suppress the electromagnetic waves from the radars by converting the incident radar energy into heat through absorption or creating destructive interference [71], [72].

The Salisbury screen [73], the Jauman absorber [74], and the Dallenbach layer [75] are well-known engineered RASs in LO applications. The Salisbury screen is one of the well-known and earliest designs in stealth technology and is made out of a dielectric substance with a quarter wavelength thickness and a metallic plate, as shown in Figure 2.2a. The metallic plate reflects the incoming EM wave, resulting in destructive interference and eliminating the incoming wave from reflecting back to the radar. The Salisbury screen's most significant flaw is its narrow frequency range.

A more advanced Jaumann absorber is used with multilayer dielectrics and resistive sheets to widen the frequency range, as shown in Figure 2.2b. Each layer is designed to target a particular frequency, and overall, the Jaumann absorber can achieve a broader absorption range. The broader the frequency range, the more layers there are to absorb waves; however, higher total structure weight comes at the expense, which is undesirable in air platforms.

The Dallenbach layer improves upon the Salisbury screen using a homogeneous lossy dielectric layer directly applied to the conductive surface. The lossy layer absorbs electromagnetic energy by combining dielectric and magnetic losses within the material. Even though the Dallenbach layer has higher absorption performance, the lossy medium limits its application for optical transparent structures. Therefore, the focus is on the Salisbury screen and Jaumann absorber in this thesis work.

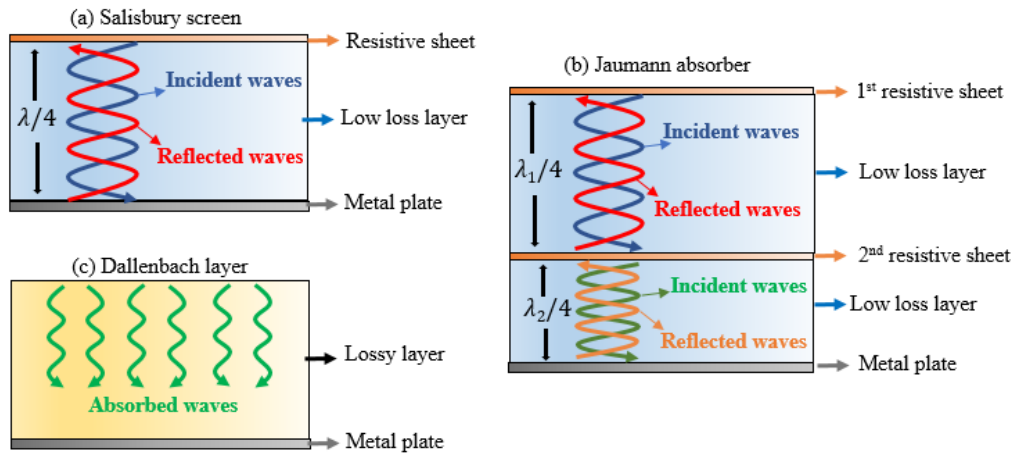


Figure 2.2. Conventional radar absorbers: (a) Salisbury screen composed of resistive sheet, low loss layer and metal plate, (b) Jaumann absorber composed of resistive layers and low loss layers with a metal plate, and (c) Dallenbach layer composed of loss layer with a metal plate.

In recent years, RASs have combined principles from Salisbury screens and Jaumann absorbers, which incorporate metamaterials [76]–[78]. Metamaterials composed of periodic patterns engineered in desired frequencies to exceed

performance limits of the conventional structures [79]. These patterns are created with modification of the planar TCO or metal layers in optically transparent RASs, resulting in metamaterials [80]–[83]. The patterns' geometry and periodicity add another design degree of freedom. This is especially important for structures with a fixed thickness due to the design constraints, which only allow their surface to be modified to enhance their performance.

Achieving the LO feature employs a combination of shape design and advanced structures, such as a combination of conventional RAS or metamaterials. Optically transparent and curved structures utilize the shape design since the primary EMI shielding mechanism in an optically transparent EMI shield is a reflection of the incoming waves. Thus, EMI shields applied to the curved structures can achieve low observability by redirecting radar signals to undetectable directions. Our effort on numerical studies based on the Salisbury screen and Jaumann absorber in the context of LO and EMI shielding will be discussed in Chapter 3, and we will realize an optically transparent EMI shield across large areas in Chapter 4.

Chapter 3

Numerical Modeling of Aviation Transparencies for Electromagnetic Interference Shielding and Low Observability

Chapter 3 explains our approach and numerical calculations to evaluate the electromagnetic responses of aviation transparencies and their thin-film-coated ones. In Chapter 2, we used polycarbonate (PC) as the aviation platform for our designs. Section 3.1. presents the electromagnetic interference (EMI) shielding and low observability (LO) performance of the mono- and multilayer PCs, while Section 3.2 further discusses the patterned monolayer counterparts.

We find it helpful to understand the experimental setup to achieve more precise numerical modeling for EMI shielding and LO performance evaluation. The free-space experimental setup comprises a network analyzer connected to *Port – 1* and *Port – 2*, with the material under test placed between the ports, as shown in

Figure 3.1. The free-space measurement setup allows us to obtain the material's scattering parameters (S -parameters) under test. The S -parameters (i.e., S_{11} , S_{22} , S_{21} , S_{12}) provide how signals are reflected from and transmitted through the material under test (MUT).

S_{21} is the transmission loss that quantifies how much of the incoming electromagnetic wave from $Port - 1$ passes through the MUT and reaches $Port - 2$. We must minimize S_{21} to achieve high EMI shielding, which in turn reduces the transmission. S_{11} is the reflection loss that gives the amount of electromagnetic wave reflected back to $Port - 1$ from the MUT. To achieve low observability, we must minimize both S_{21} and S_{11} . Therefore, we focused on S_{21} and S_{11} in the numerical calculations to evaluate structures' EMI shielding and LO features. The S -parameters can be expressed in decibels (dB) and linear scale using the following relations:

$$S_{21}(dB) = 20\log_{10}(S_{21}(linear)) \quad (3.1)$$

$$S_{11}(dB) = 20\log_{10}(S_{11}(linear)) \quad (3.2)$$

Using $S_{21}(linear)$ complex transmission coefficient and $S_{11}(linear)$ complex reflection coefficient, the transmittance and reflectance can be calculated as:

$$T = \frac{P_{transmitted}}{P_{incident}} = |S_{21}|^2 \quad (3.3)$$

$$R = \frac{P_{reflected}}{P_{incident}} = |S_{11}|^2 \quad (3.4)$$

where $P_{incident} = P_{transmitted} + P_{reflected} + P_{absorbed}$. We can therefore calculate the absorbance as:

$$A = 1 - (T + R) \quad (3.5)$$

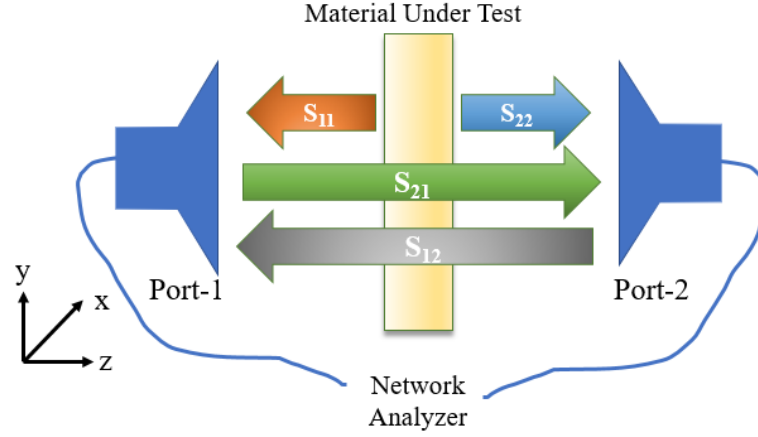


Figure 3.1. Free-space measurement system, which utilizes a network analyzer connected to Port – 1 and Port – 2, shown along with the S -parameters (i.e., S_{11} , S_{22} , S_{21} , S_{12}). The material under test is placed between the ports.

CST Microwave Studio is used in the numerical calculations utilizing the unit-cell module. In the unit-cell module, the electromagnetic wave propagates in the z -direction (indicated in Figure 3.2) , and the structure is periodic in the x - and y -directions, as shown in Figure 3.2a.

The complex permittivity ($\epsilon = \epsilon' - j\epsilon''$) and the complex permeability ($\mu = \mu' - j\mu''$) determine the electromagnetic characteristics of a material in terms of reflection, transmission, and absorption. Magnetic materials have high permeability and provide effective EMI shielding and LO performance primarily through absorption [84]. However, since magnetic fillers incorporated in polymers are optically opaque [85], [86], and even nanometer-thick magnetic films have low transmission in the visible spectrum [87], in this thesis we focus on non-magnetic materials (*i.e.*, $\mu = 1$) in our designs.

The real part of the dielectric constant (ϵ') represents how much electric energy the material can store, which changes the phase velocity and wavelength of

electromagnetic waves propagating through it. The higher the dielectric constant, the slower the electromagnetic waves travel through the material, thereby altering their phase. The imaginary part of the dielectric constant (ϵ'') accounts for the loss of energy, which causes waves to be absorbed. The higher the imaginary part, the more the absorbed electromagnetic wave [88]. Both the real and imaginary parts affect reflection by creating impedance mismatch, which affects the material's electromagnetic characteristics [89].

We extracted the complex permittivity of PC from S -parameters using a free-space measurement system, as shown in Figure 3.2b, and then imported it into CST Microwave Studio for the numerical calculations. We performed our numerical calculations within the frequency range of 1 to 20 GHz, which corresponds to the wavelength range of 300 to 15 mm. We defined thin-film coatings as the resistive films since the wavelength range is significantly longer than the thin-film coating thickness in the nanometer range. We assumed a uniform thickness of the thin-film coating, resulting in a constant sheet resistance value of the resistive films.

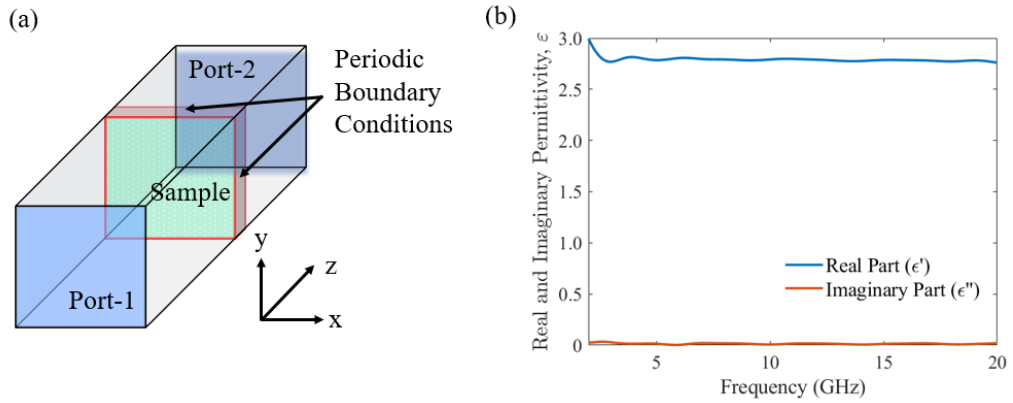


Figure 3.2. (a) CST Microwave Studio 3D schematics of the unit-cell setup used in our numerical calculations. The setup includes material under test placed between *Port* – 1 and *Port* – 2. (b) Complex permittivity ($\epsilon = \epsilon' - j\epsilon''$) of PC in the frequency range of 2–20 GHz extracted from S -parameters.

3.1. Monolayer and Laminated Structures

Section 3.1 investigates the electromagnetic behavior of monolayer and laminated PCs and their thin film-coated designs. We first studied the thin films with different sheet resistance values. Next, we applied the findings to PCs in monolayer form with different thickness values. Finally, we extended the numerical studies to the laminated form, investigating their RF performances in terms of EMI shielding and LO. The term monolayer here refers to a single PC substrate, while the laminated refers to the class of laminated PC layers. The presence of the thin films does not influence a layer's classification as the monolayer or the laminated.

An electromagnetic wave interacting with a material can be reflected, be transmitted, and be absorbed by a fraction of its power. Figure 3.3 illustrates the relationship between S -parameters and the fractions of reflected, transmitted and absorbed power. We analyze transmission loss (S_{21}) and reflection loss (S_{11}), to determine the effectiveness of a material in reflecting, transmitting, or absorbing electromagnetic energy. To ensure that 99% or higher portion of the electromagnetic waves is not transmitted through a structure, using equation (3.3), the transmission loss (S_{21}) value must be -20 dB or less ($S_{21} \leq -20\text{ dB}$). Structures that meet this condition provide effective EMI shielding by reflecting and absorbing the incoming waves.

A structure must either absorb the electromagnetic waves or reflect them in non-detectable directions to feature an effective LO. Planar structures reflect the incoming waves in the opposite direction of the incoming waves, making them detectable and lowering LO performance based on (3.4) and (3.5). Therefore, planar structures can't effectively perform LO if the primary EMI shielding

mechanism is reflection. One approach is to design structures in such a way that they reflect electromagnetic waves in non-detectable directions to feature both EMI shielding and LO.

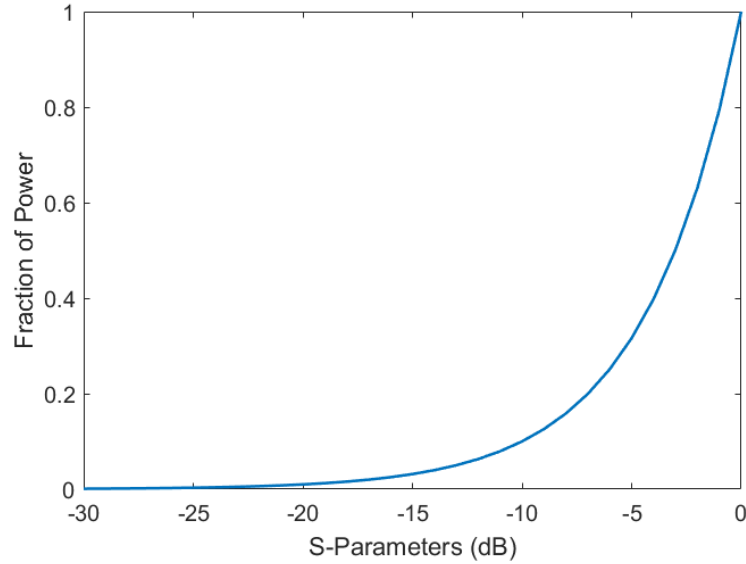


Figure 3.3. Relationship between the scattering parameters (S -parameters) and the fraction of power.

First, we numerically investigated how well a thin film layer with sheet resistance values between $10 \Omega/\square$ and $150 \Omega/\square$ blocks EMI waves in the frequency range of 1 to 20 GHz, as shown in Figure 3.4. The numerically calculated transmission loss (S_{21}) values showed that conductive layers with sheet resistance values of $10 \Omega/\square$, $15 \Omega/\square$, and $20 \Omega/\square$ block more than 99% ($S_{21} \leq -20 \text{ dB}$) of the EM wave across the associated frequency range. The conductive layers with sheet resistance values of $25 \Omega/\square$, $30 \Omega/\square$, $35 \Omega/\square$, $40 \Omega/\square$, $45 \Omega/\square$, $50 \Omega/\square$, $100 \Omega/\square$, and $150 \Omega/\square$ cannot provide EMI shielding over 99% since they do not satisfy $S_{21} \leq -20 \text{ dB}$. It should be noted that the transmission loss does not change across the frequency range since the sheet resistance value is set constant throughout the frequency range.

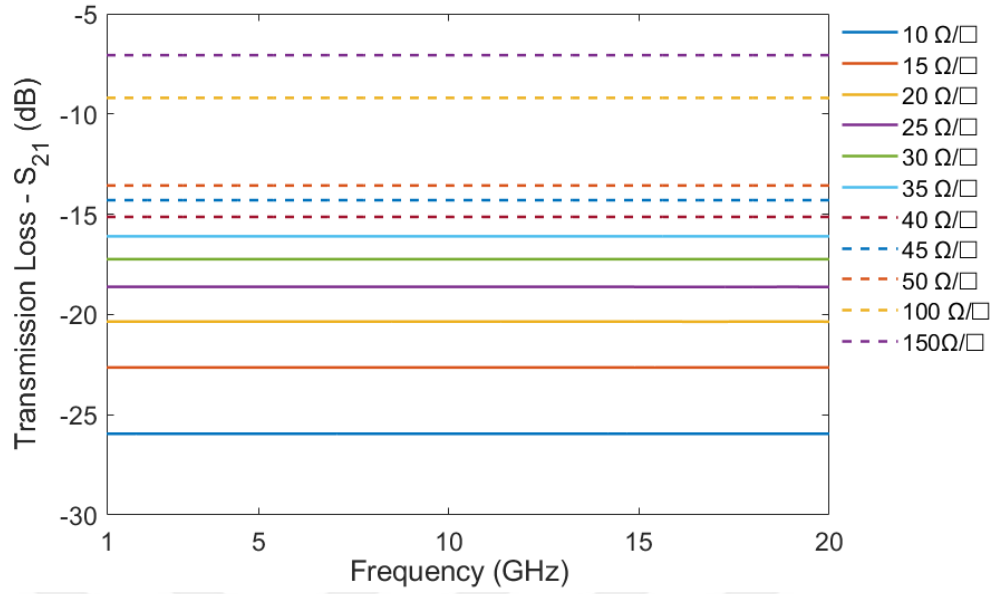


Figure 3.4. Numerically calculated spectral transmission loss (dB) of conductive films with sheet resistance values of 10 $\Omega/\square$, 15 $\Omega/\square$, 20 $\Omega/\square$, 25 $\Omega/\square$, 30 $\Omega/\square$, 35 $\Omega/\square$, 40 $\Omega/\square$, 45 $\Omega/\square$, 50 $\Omega/\square$, 100 $\Omega/\square$, and 150 $\Omega/\square$ across 1–20 GHz.

We numerically calculated the transmission loss of the uncoated PC with different thickness values to evaluate their EMI shielding performance across 1–20 GHz, as shown in Figure 3.5. The average transmission loss across 1–20 GHz for different thickness values (1–12 mm) is calculated as -0.23 dB, -0.62 dB, -0.81 dB, -0.76 dB, -0.65 dB, -0.68 dB, -0.78 dB, -0.81 dB, -0.76 dB, -0.75 dB, -0.80 dB, and -0.85 dB, respectively. These results indicate that uncoated PC with thickness values between 1–12 mm transmits a significant portion of the electromagnetic wave, resulting in poor EMI shielding across this frequency range. This transmission is mainly due to the low ϵ'' value of the PC substrate in 1–20 GHz, as shown in Figure 3.2b.

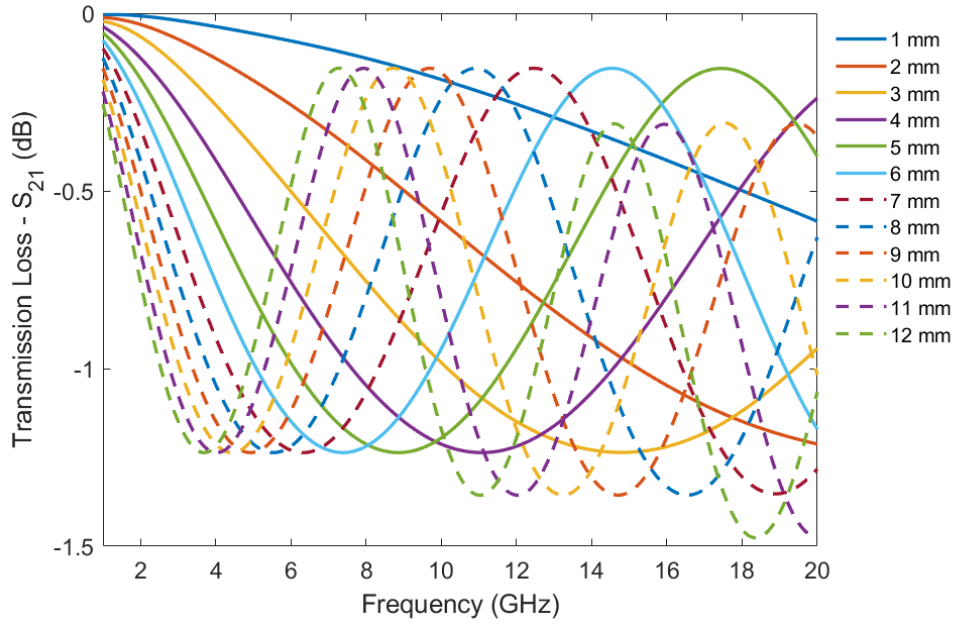


Figure 3.5. Numerically calculated spectral transmission loss (dB) of uncoated PC monolayers with varying thickness values between 1–12 mm across 1–20 GHz.

To increase the EMI shielding performance of the uncoated PC, a conductive layer with a sheet resistance value of $10 \Omega/\square$ was applied to the PC. The numerically calculated transmission and reflection losses of the conductive layer-coated PC are given in Figures 3.6 and 3.7, respectively. The resonant frequency shifts toward lower frequencies for both reflection and transmission losses as the PC thickness increases. This shift occurs due to the increased path length of electromagnetic waves within the structure in accordance with the quarter wavelength principle [90].

The results show that the structure blocks over 99% ($S_{21} \leq -20 \text{ dB}$) of electromagnetic waves, no matter how thick the PC is, thanks to the $10 \Omega/\square$ conductive layer. On the other hand, the average reflection losses (S_{11}) in 1–20 GHz for different thickness values (1–12 mm) were calculated as -0.51 dB, -0.77 dB, -0.99 dB, -0.95 dB, -0.89 dB, -0.90 dB, -1.04 dB, -1.08 dB, -1.05 dB, -1.04 dB, -1.13 dB, and -1.21 dB, respectively. Using (3.2) and (3.4), the reflection

values were calculated as 89.13%, 84.13%, 79.44%, 80.10%, 81.00%, 80.84%, 78.27%, 77.69%, 78.19%, 78.27%, 77.01%, and 75.91%, respectively. This means the structure reflects most of the electromagnetic waves that impinge on it. The low reflection loss values across the 1–20 GHz frequency range indicate that a reflection mechanism provides the EMI shielding. Since the thickness of the conductive layer is expected to be lower than the skin depth in the GHz regime, the EMI shielding occurs primarily by reflection [91].

This high level of reflection is not desirable for low observability applications. For low observability, high reflection loss (S_{11}) is required together with a high transmission loss (S_{21}), as previously explained. The Salisbury Screen design principle, described in Chapter 2, guides the engineering of the PC substrate with resistive and conductive layers, as depicted in Figure 3.8, with the aim of minimizing reflection to the greatest extent possible. In Figure 3.8, the green layers, representing resistive and conductive layers, are infinitely thin in comparison to the blue-colored substrate layer.

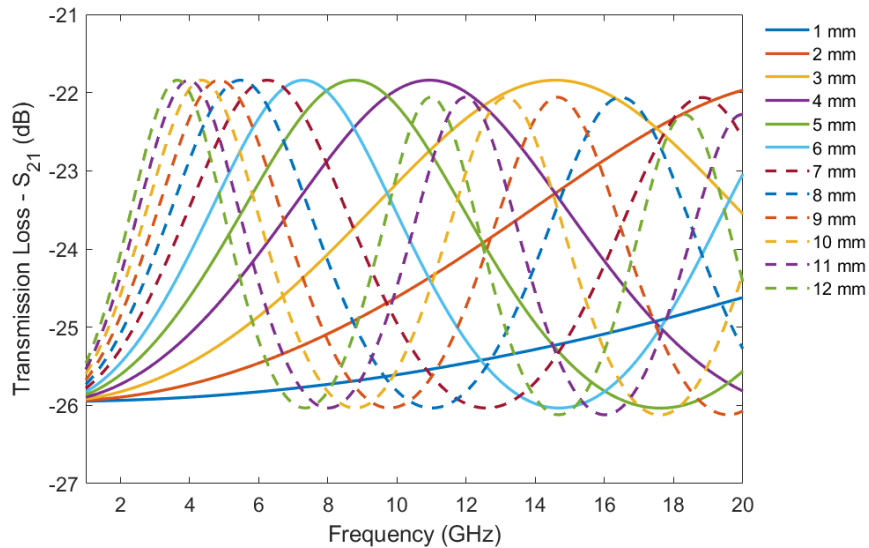


Figure 3.6. Numerically calculated spectral transmission loss (dB) of the conductive layer with a sheet resistance value of $10 \Omega/\square$, applied to the PC substrate with varying thickness values between 1–12 mm across 1–20 GHz.

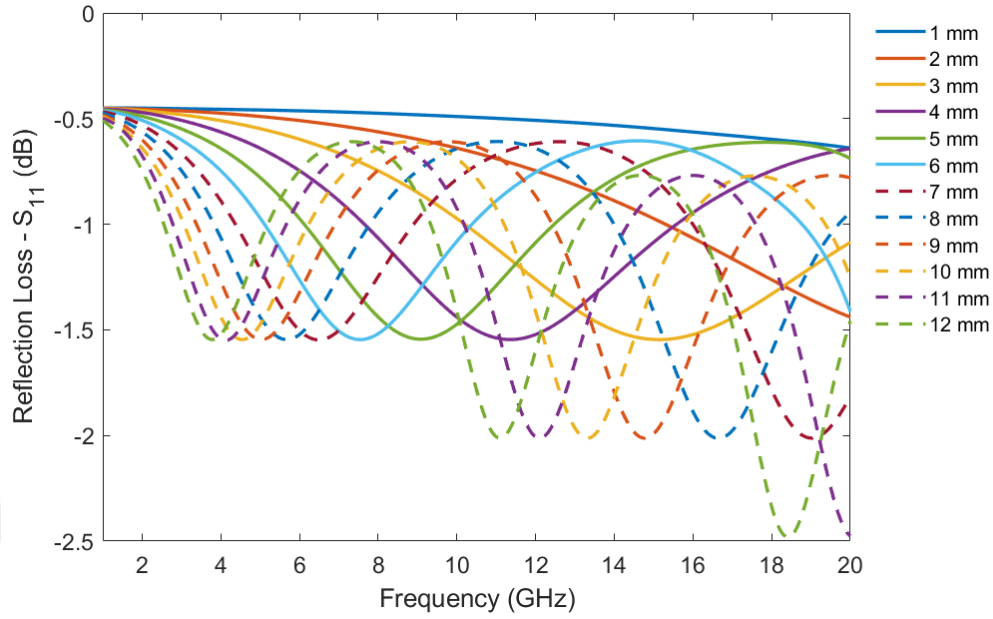


Figure 3.7. Numerically calculated spectral reflection loss (dB) of the conductive layer with a sheet resistance value of $10 \Omega/\square$, applied to the PC substrate with varying thickness values between 1–12 mm across 1–20 GHz.

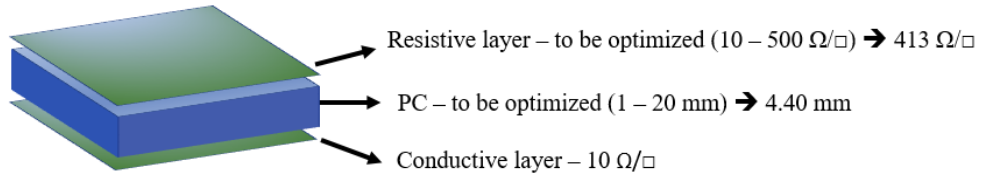


Figure 3.8. Schematic of the structure to be optimized based on the Salisbury Screen. The structure composed of resistive and conductive layers (shown in green) applied to the top and bottom of the PC monolayer (shown in blue).

We used CST Microwave Studio optimization tools to optimize the thickness of the PC substrate and the sheet resistance of the resistive layer. The conductive layer at the bottom with a sheet resistance value of $10 \Omega/\square$ was not changed to sustain a high level of EMI shielding. We utilized the trust region numerical optimization method to enhance absorption in the range of 1–20 GHz. The sheet resistance value of the resistive layer was optimized between 10 and $500 \Omega/\square$, and the PC thickness was optimized between 1–12 mm.

The thickness of the PC layer was optimized to be 4.40 mm and the sheet resistance of resistive layer is optimized to be $413 \Omega/\square$. The transmission losses and reflection losses of the optimized structure, with and without the resistive layer, are given in Figure 3.9. Both 4.4 mm PC + $10 \Omega/\square$ and $413 \Omega/\square$ + 4.40 mm PC + $10 \Omega/\square$ satisfy the EMI shielding condition of $S_{21} \leq -20 \text{ dB}$ as expected owing to the $10 \Omega/\square$ conductive layer. The average transmission loss of $413 \Omega/\square$ + 4.40 mm PC + $10 \Omega/\square$ is -26.72 dB and -24.07 dB for 4.40 mm PC + $10 \Omega/\square$. This indicated that the structure with the resistive layer relatively has a higher level of EMI shielding compared to the structure without the resistive layer.

Figure 3.9 compares the reflection losses at 10 GHz of optimized structure with and without the resistive layer, which were calculated -1.5 dB and -60 dB, respectively. The resistive layer at the top was utilized for the impedance matching that allows incoming electromagnetic waves to pass through the structure. The sharp resonance at 10 GHz of the structure with the resistive layer is due to the destructive interference.

We calculated transmittance, reflectance, and absorbance of the structures from the reflection loss and the transmission loss using (3.1–3.5), as shown in Figure 3.10. The optimized structure, 4.40 mm PC + $10 \Omega/\square$, transmits 0.41% of the electromagnetic wave in the 1–20 GHz range and reflects 81.08%, while the remaining 18.51% is absorbed. The optimized structure, $413 \Omega/\square$ + 4.40 mm PC + $10 \Omega/\square$, transmits 0.21% of the electromagnetic wave in the 1–20 GHz range and reflects 39.67%, while the remaining 60.11% is absorbed. Adding the resistive layer does not affect the transmittance along the frequency range, while absorption increases due to the destructive interference effect.

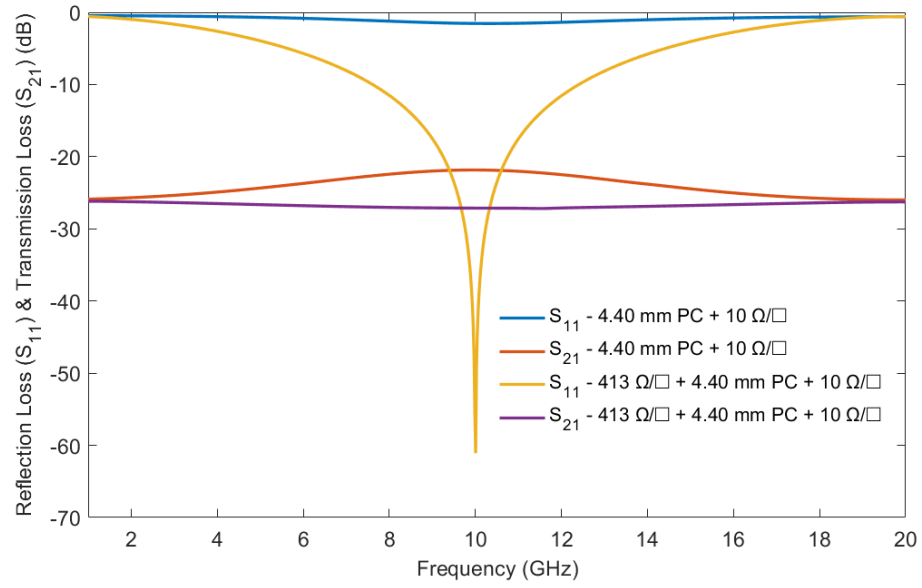


Figure 3.9. Numerically calculated reflection loss (dB) and transmission loss (dB) of the optimized structures 4.40 mm PC + 10 $\Omega/\square$ and 413 $\Omega/\square$ + 4.40 mm PC + 10 $\Omega/\square$ across 1–20 GHz.

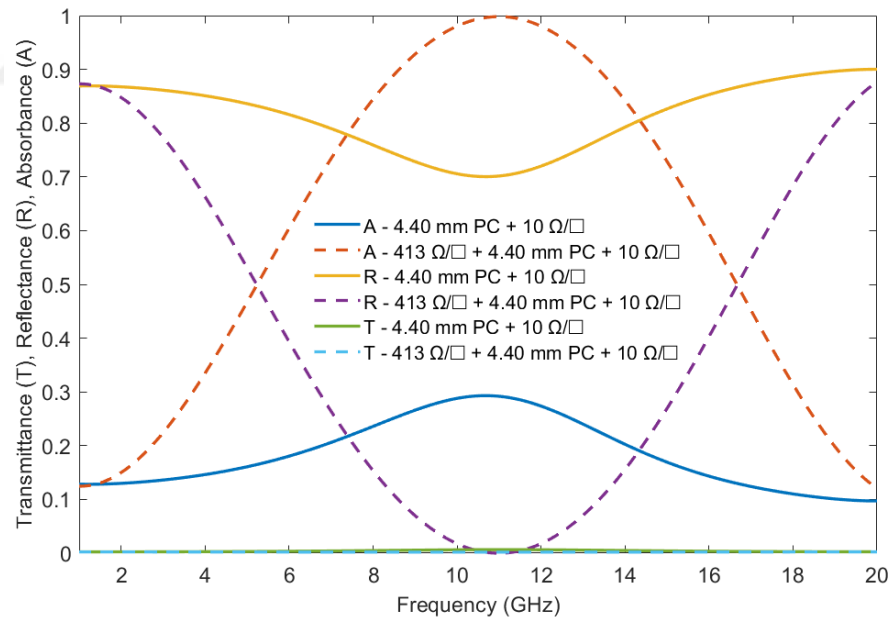


Figure 3.10. Numerically calculated transmittance, reflectance and absorbance of the optimized structures 4.40 mm PC + 10 $\Omega/\square$ and 413 $\Omega/\square$ + 4.40 mm PC + 10 $\Omega/\square$ across 1–20 GHz.

The electromagnetic response of the optimized structure was also studied for oblique angles and in different polarizations. Since the interaction of the electromagnetic wave at a normal angle is different for oblique angles and polarizations, it can affect the structure's transmission, reflection, and absorption properties. Therefore, we studied the EMI shielding and LO features of the optimized structure for different polarizations at oblique angles in the range of 1–20 GHz.

The reflection loss and the transmission loss of the $413 \Omega/\square + 4.40 \text{ mm PC} + 10 \Omega/\square$ structure for both the horizontal (H-pol) and vertical (V-pol) polarizations at oblique angles, were calculated in 1–20 GHz, as shown in Figures 3.11 and 3.12, respectively. The structure satisfies over 99% EMI shielding ($S_{21} \leq -20 \text{ dB}$) for both the horizontal and vertical polarizations at the incidence angles of 15° , 30° , 45° , and 60° , as summarized in Table 3.1.

As the angle of incidence increases from 0° to 60° for the vertical polarization, the structure's reflection of the electromagnetic wave decreases while the transmitted wave increases. The decrease in the reflection for the vertically polarized waves as the angle of incidence increases is consistent with Fresnel equations. Since the rate of decrease in reflection is higher than the rate of increase in transmission, the absorption increases as the angle of incidence increases.

Conversely, with horizontal polarization, the transmitted electromagnetic wave decreases as the angle of incidence increasing from 0° to 60° . The reflection decreases up to 30° , further increasing the angle of incidence, which results in the reflection increasing while absorption decreases.

Table 3.1. Average transmission (T%), reflection (R%), and absorption (A%) of the optimized structure ($413 \Omega/\square + 4.40 \text{ mm PC} + 10 \Omega/\square$) in 1–20 GHz at different angles of incidence ($0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ$) for the H- and V-polarizations.

413 ohm-per-sq / 4.40 mm PC / 10 ohm-per-sq						
Angle of Incidence	Vertical Polarization (V-pol)			Horizontal Polarization (H-pol)		
	T%	R%	A%	T%	R%	A%
$\theta = 0^\circ$	0.21	39.67	60.12	0.21	39.67	60.12
$\theta = 15^\circ$	0.23	38.82	60.95	0.20	39.39	60.41
$\theta = 30^\circ$	0.27	36.39	63.34	0.17	38.90	60.93
$\theta = 45^\circ$	0.36	33.10	66.54	0.12	39.59	60.29
$\theta = 60^\circ$	0.56	31.45	67.99	0.07	44.83	55.10

These results indicate that monolayer structures can provide EMI shielding over 99% while further enhancing LO requires additional configurations. Low transmittance and low reflectance are required to increase the low observability performance. Based on Jaumann's design principles, we upgraded the monolayer structure with an additional PC layer and a resistive layer to enhance LO performance, as shown in Figure 3.13.

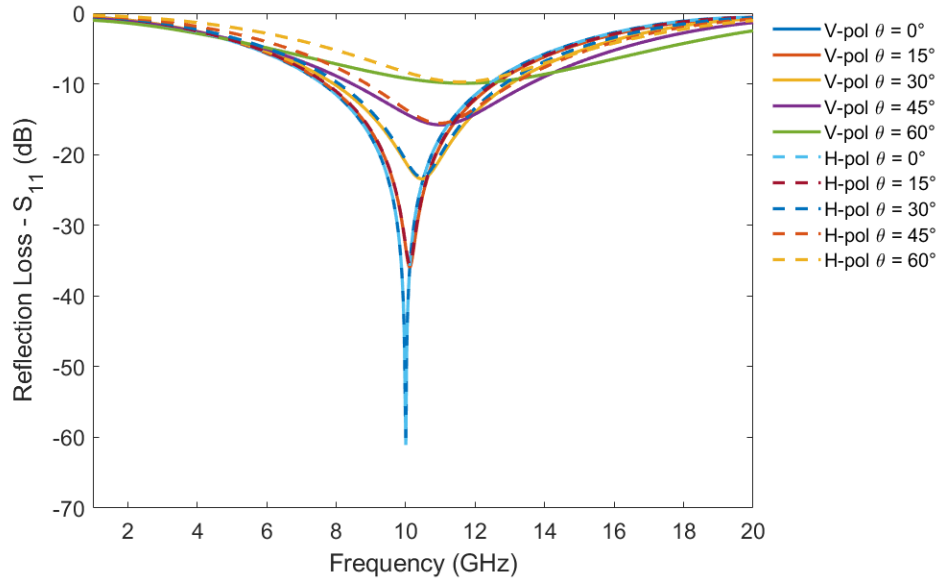


Figure 3.11. Numerically calculated spectral reflection loss (dB) of the optimized structure ($413 \Omega/\square + 4.40 \text{ mm PC} + 10 \Omega/\square$) in 1–20 GHz at different angles of

incidence (0° , 15° , 30° , 45° , 60°) for the vertical (V-pol) and horizontal (H-pol) polarizations.

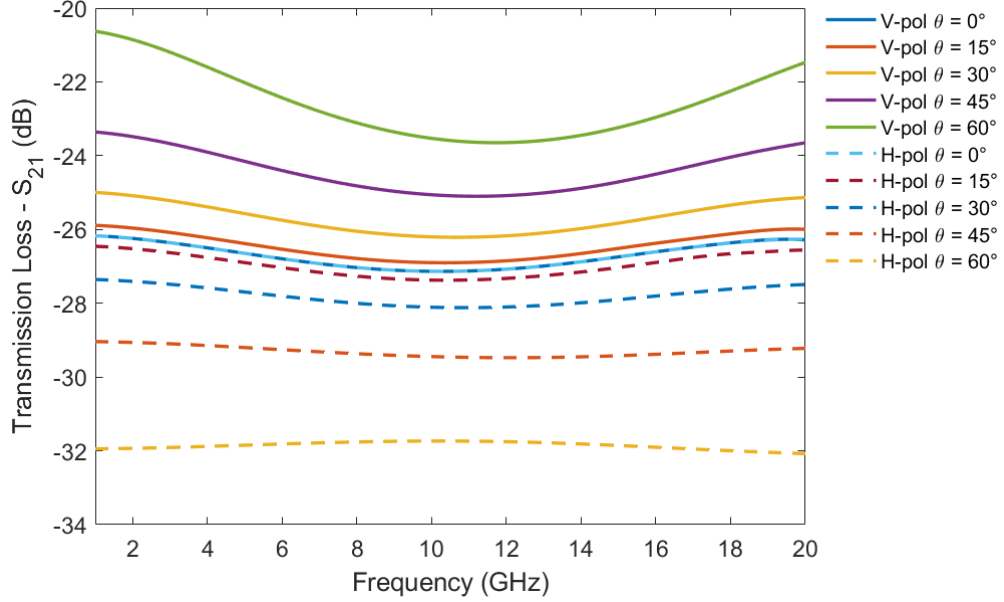


Figure 3.12. Numerically calculated spectral transmission loss (dB) of the optimized structure ($413 \Omega/\square$ + 4.40 mm PC + $10 \Omega/\square$) in 1–20 GHz at different angles of incidence (0° , 15° , 30° , 45° , 60°) for the vertical (V-pol) and horizontal (H-pol) polarizations.

The laminated structure's 1st and 2nd PC thickness and the 1st resistive film were optimized to enhance absorption in 1–20 GHz. The conductive film was not included in the optimization process and set to $10 \Omega/\square$ to ensure EMI shielding across the frequency range. We used the trust region optimization algorithm, similar to the monolayer optimization, to maximize absorption in the 1–20 GHz range. The sheet resistance value of the resistive layers is optimized between $10 \Omega/\square$ and $500 \Omega/\square$, and the thickness of the PC layers is optimized between 1–12 mm. The thicknesses of the 1st and 2nd PC layers were optimized to 4.40 mm, and the sheet resistance value of the 1st resistive layer is $150 \Omega/\square$ to yield high absorption in 1–20 GHz.

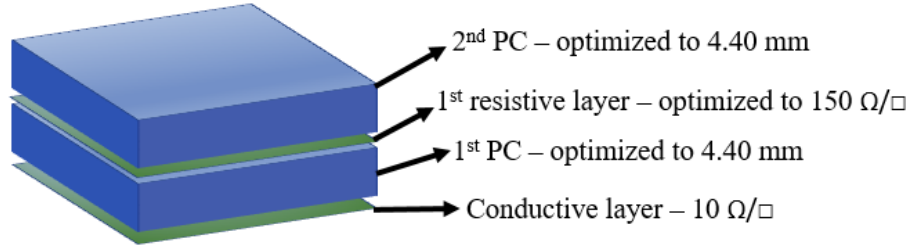


Figure 3.13. Schematic of the structure to be optimized based on Jaumann design principle. The structure is composed of resistive layers (shown in green) applied to the top and bottom of the PC substrate (shown in blue).

The reflection and transmission losses of the laminated structure, 4.40 mm PC + 150 $\Omega/\square$ + 4.40 mm PC + 10 $\Omega/\square$, for the vertical and horizontal polarizations at the angles of 0°, 15°, 30°, 45°, and 60° were numerically calculated and given in Figures 3.14 and 3.15, respectively. The average reflection, transmission, and absorption of the laminated structure were calculated using (3.1–3.5) and are summarized in Table 3.2. The laminated structure satisfies over 99% EMI shielding ($S_{21} \leq -20$ dB) for both the horizontal and vertical polarizations at the incidence angles of 15°, 30°, 45°, and 60°, as shown in Table 3.2.

Notably, the transmission loss for the horizontal polarization decreases with an increase in the angle of incidence, while for the vertical polarization, the transmission loss increases proportionally to the angle of incidence. This transmission characteristic of the laminated structure also occurred in the monolayer structure, which was previously explained by Fresnel equations. The electromagnetic characteristics of both monolayer and laminated structures are identical, showing no difference between the horizontal and vertical polarizations at normal angles, or when the angle of incidence is zero degree.

The difference between transmission values of monolithic and laminated structures at oblique angles for both polarizations is less than 0.1%. Therefore, the destructive interference leading to absorption between the laminated PC layers is responsible for the decrease in reflection. The absorption of the

laminated structure, 4.40 mm PC + 150 $\Omega/\square$ + 4.40 mm PC + 10 $\Omega/\square$, is 15% higher than the monolithic structure, 4.40 mm PC + 10 $\Omega/\square$, at oblique angles for both polarizations.

We showed that monolithic and laminated structures feature over 99% EMI shielding thanks to the 10 $\Omega/\square$, while the LO performance of the laminated structures is superior. The disadvantage of the laminated structure is the increased weight due to the higher number of layers and fabrication complexity. In design, changing the substrate's geometrical properties, such as thickness, may not be possible. The following Section 3.2 presents a patterned resistive layer for monolithic structures to enhance their EMI shielding and LO performances.

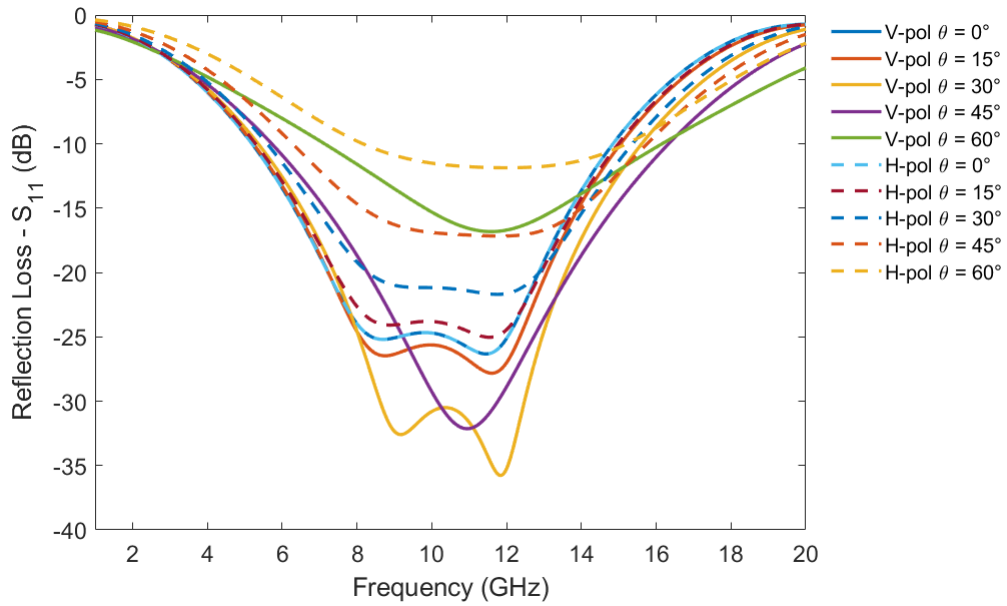


Figure 3.14. Numerically calculated spectral reflection loss (dB) of the laminated structure (4.40 mm PC + 150 $\Omega/\square$ + 4.40 mm PC + 10 $\Omega/\square$) in 1–20 GHz at different angles of incidence (0°, 15°, 30°, 45°, 60°) for the vertical (V-pol) and horizontal (H-pol) polarizations.

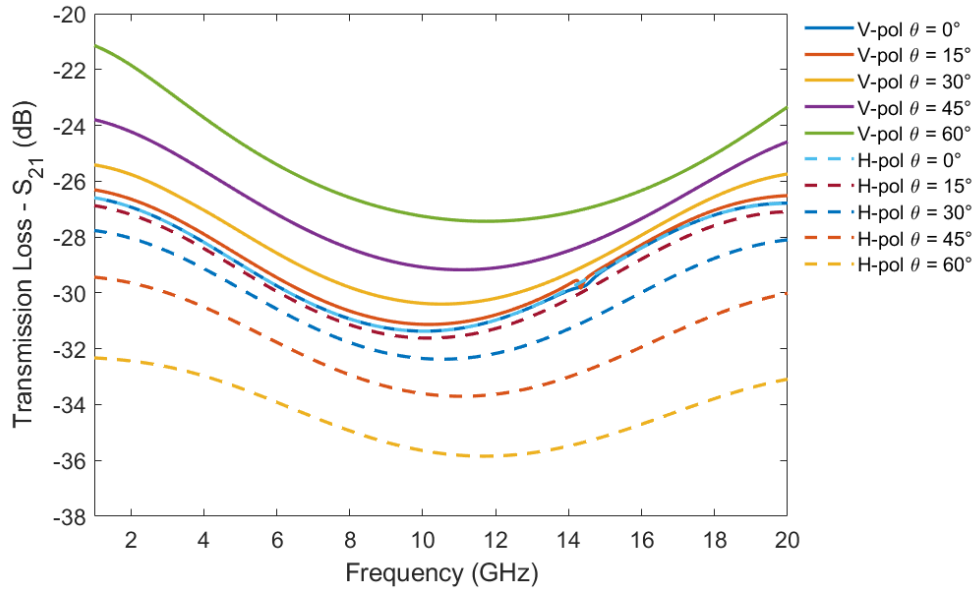


Figure 3.15. Numerically calculated spectral transmission loss (dB) of the laminated structure (4.40 mm PC + 150 $\Omega/\square$ + 4.40 mm PC + 10 $\Omega/\square$) in 1–20 GHz at different angles of incidence (0°, 15°, 30°, 45°, 60°) for the vertical (V-pol) and horizontal (H-pol) polarizations.

Table 3.2. Average transmission (T%), reflection (R%), and absorption (A%) of the laminated structure (4.40 mm PC + 150 $\Omega/\square$ + 4.40 mm PC + 10 $\Omega/\square$) in 1–20 GHz at different angles of incidence (0°, 15°, 30°, 45°, 60°) for the H- and V-polarizations.

Angle of Incidence	4.40 mm PC + 150 $\Omega/\square$ + 4.40 mm PC + 10 $\Omega/\square$					
	Vertical Polarization (V-pol)			Horizontal Polarization (H-pol)		
	(T%)	(R%)	(A%)	(T%)	(R%)	(A%)
$\theta = 0^\circ$	0.13	24.42	75.45	0.13	24.42	75.45
$\theta = 15^\circ$	0.14	23.44	76.43	0.12	23.97	75.91
$\theta = 30^\circ$	0.16	20.76	79.08	0.10	22.96	76.95
$\theta = 45^\circ$	0.21	17.81	81.98	0.07	22.85	77.08
$\theta = 60^\circ$	0.31	18.42	81.27	0.04	27.22	72.74

3.2. Patterned Structures – Metasurfaces

In Section 3.2, a metasurface is added to the previously optimized monolayer design, which is 4.40 mm PC + 10 $\Omega/\square$, to further enhance its absorption performance without changing PC thickness in 1–20 GHz. The metasurface is placed to the top of the optimized structure as a resistive layer and composed of a patterned periodic single square structure, as shown in Figure 3.16a. The thickness of the PC is set to 4.40 mm, and the sheet resistance layer of the planar layer is fixed to 10 $\Omega/\square$.

The geometrical parameters of the metasurface to be optimized are unit cell size (a), outer edge length (b), inner edge length (c), gap width (d), and width of the single square frame (e), as shown in Figure 3.16b. We used the genetic algorithm (GA) method of the CST Microwave Studio optimization tool to optimize these parameters for the highest absorption in 1–20 GHz. We used GA instead of the trust region algorithm, which we used in Section 3.1, since the geometrical parameters of the metasurface exhibit non-linear behavior [92].

The parameters were optimized as follows: $a = 10.29\text{ mm}$, $b = 7.85\text{ mm}$, $c = 6.79\text{ mm}$, $d = 2.44\text{ mm}$, $e = 0.53\text{ mm}$. The sheet resistance value of the patterned layer is found to be 16 $\Omega/\square$. The top-view, bottom-view of the unit cell and the perspective view of the representative structure in which the unit cell is periodic in x - and y - directions, are shown in Figures 3.16(c-e), respectively.

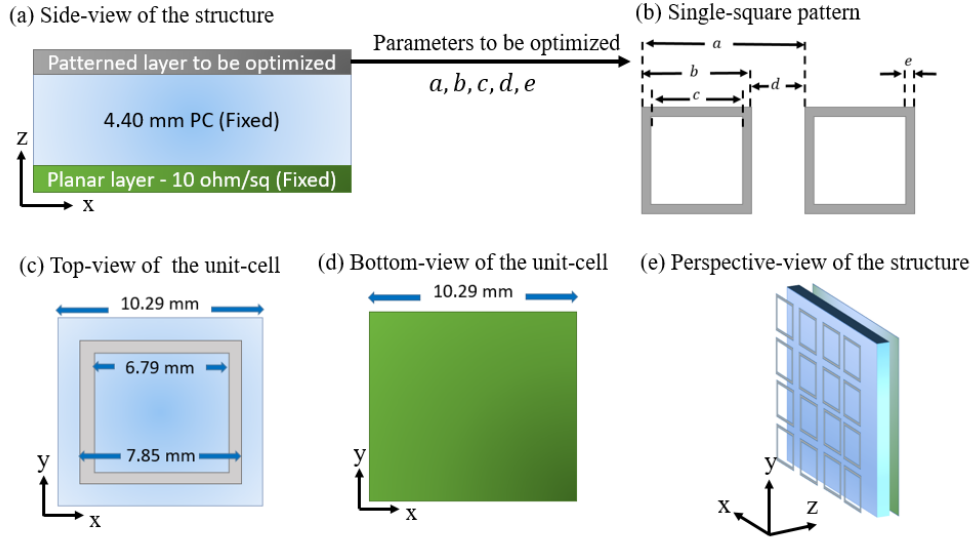


Figure 3.16. (a) Side-view of the structure, (b) geometrical parameters (a, b, c, d, e) of the single-square pattern to be optimized, (c) the top view and (d) the bottom view of the unit cell, and (e) the perspective view of the structure.

The reflection loss and the transmission loss of the $16 \Omega/\square$ patterned layer + 4.40 mm PC + $10 \Omega/\square$ planar layer for both the H- and V-polarizations at oblique angles ($15^\circ, 30^\circ, 45^\circ, 60^\circ$) were calculated in 1–20 GHz, as shown in Figures 3.17 and 3.18, respectively. In Figure 3.17, the reflection loss at 10 GHz is -70 dB for the angle of incidence 0° . As the angle of incidence increases, the resonance frequency shifts toward higher frequencies, while the reflection decreases for the V-pol and increases for the H-pol. The increase in the reflection of horizontally polarized electromagnetic waves at higher incidence angles limits the absorption since the transmission does not change much.

The average transmission, reflection, and absorption in 1–20 GHz were calculated using (3.1–3.5) through spectral reflection loss and transmission loss for oblique angles and the H- and V-polarizations, given in Table 3.3. In Figure 3.18, the structure satisfies over 99% EMI shielding ($S_{21} \leq -20 \text{ dB}$) for both polarizations at the incidence angles of $0^\circ, 15^\circ, 30^\circ, 45^\circ$, and 60° across the frequency range of 1–20 GHz.

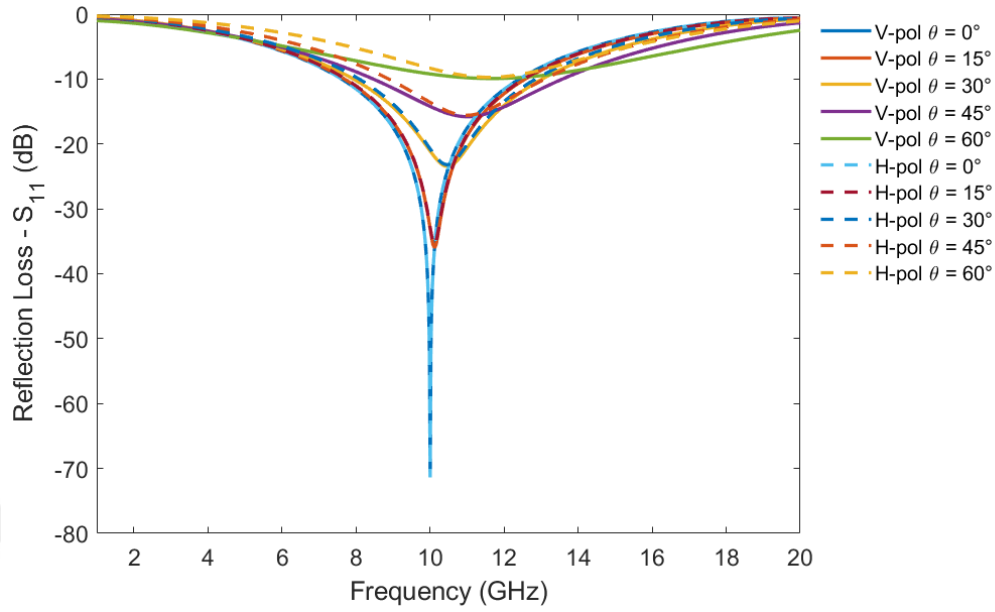


Figure 3.17. Numerically calculated spectral reflection loss (dB) of the patterned structure ($16 \Omega/\square$ patterned layer + 4.40 mm PC + $10 \Omega/\square$ planar layer) in 1–20 GHz at different angles of incidence (0° , 15° , 30° , 45° , 60°) for the vertical (V-pol) and the horizontal (H-pol) polarizations.

Lastly, numerically calculated spectral absorption of the PC, PC + $10 \Omega/\square$, $413 \Omega/\square$ + PC + $10 \Omega/\square$, $16 \Omega/\square$ + PC, and $16 \Omega/\square$ + PC + $10 \Omega/\square$ in the frequency range of 1–20 GHz at normal angle are given for comparison purposes, as shown in Figure 3.19. The thickness of the PC is fixed to 4.40 mm for all structures. Without resistive layers, the PC absorbs 1.63% of the electromagnetic waves in the frequency range of 1–20 GHz. Adding a planar $10 \Omega/\square$ bottom conductive layer increases absorption to 18.51% creating a destructive interference based on the Salisbury Screen. Then, the planar $413 \Omega/\square$ top resistive layer was added to 4.4 mm PC + $10 \Omega/\square$ to further increase the absorption to 60.14% through impedance matching [93].

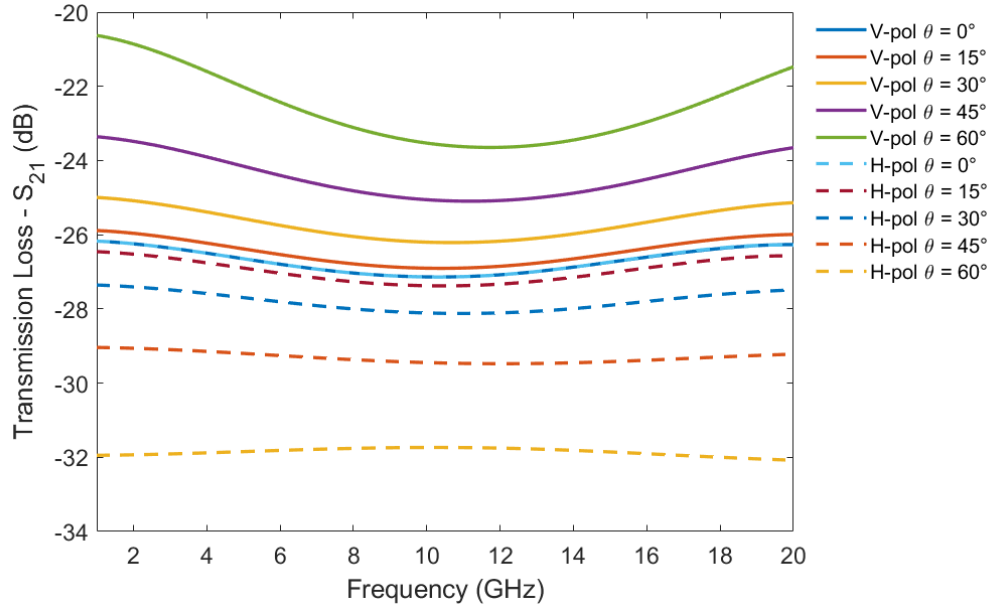


Figure 3.18. Numerically calculated spectral transmission loss (dB) of the patterned structure ($16 \Omega/\square$ patterned layer + 4.40 mm PC + $10 \Omega/\square$ planar layer) in 1–20 GHz at different angles of incidence (0° , 15° , 30° , 45° , 60°) for the vertical (V-pol) and horizontal (H-pol) polarizations.

The design includes a single square pattern metasurface to exceed the absorption limit of 60.14% conventional planar film-coated structures in monolayers. The findings show that the absorption increases to 65.15% for $\theta = 0^\circ$, as a result of electrical resonances caused by the gaps between patterns [94]. A reflective layer with a sheet resistance value of $10 \Omega/\square$ is necessary for effective absorption, as the top patterned layer alone absorbs 21.99% in 1–20 GHz. The metasurface added monolayer PC structure also exhibits higher absorption performance compared to the planar counterpart at oblique angles of 15° , 30° , 45° , and 60° for the H- and V-polarizations since the single-square pattern has fourfold symmetry [95].

Table 3.3. Average transmission (T%), reflection (R%), and absorption (A%) of the laminated structure (16 $\Omega/\square$ patterned layer + 4.40 mm PC + 10 $\Omega/\square$ planar layer) in 1–20 GHz at different angles of incidence (0°, 15°, 30°, 45°, 60°) for the H- and V-polarizations.

Angle of Incidence	16 $\Omega/\square$ Patterned Layer + 4.40 mm PC + 10 $\Omega/\square$ Planar Layer					
	Vertical Polarization (V-pol)			Horizontal Polarization (H-pol)		
	T%	R%	A%	T%	R%	A%
$\theta = 0^\circ$	0.25	34.60	65.15	0.25	34.60	65.15
$\theta = 15^\circ$	0.26	33.83	65.91	0.24	34.46	65.30
$\theta = 30^\circ$	0.31	31.55	68.14	0.20	34.79	65.01
$\theta = 45^\circ$	0.41	28.79	70.80	0.14	35.87	63.99
$\theta = 60^\circ$	0.62	28.33	71.05	0.08	41.28	58.64

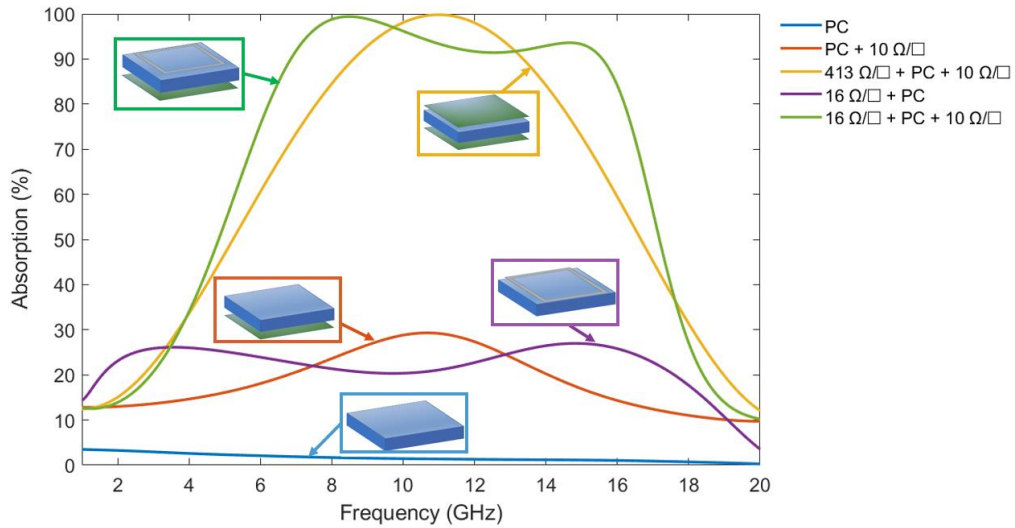


Figure 3.19. Numerically calculated absorption of the PC, PC + 10 $\Omega/\square$, 413 $\Omega/\square$ + PC + 10 $\Omega/\square$, 16 $\Omega/\square$ + PC, and 16 $\Omega/\square$ + PC + 10 $\Omega/\square$ in the frequency range of 1–20 GHz at normal angle ($\theta = 0^\circ$). The thickness of the monolayer PC is 4.40 mm for all structures.

In Chapter 3, we engineered monolayer and laminated structures to provide EMI shielding and LO features. Firstly, we numerically calculated the transmission loss of films that can satisfy EMI shielding over 99% and used them as a reflective layer, similar to the Salisbury Screen. Then, a conductive film with a sheet

resistance value of $10 \Omega/\square$ was added to the PC at different thicknesses to investigate its EMI shielding and LO performance. Implementing $10 \Omega/\square$ to the structure makes it possible to shield electromagnetic waves in 1–20 GHz through reflection; it has the disadvantage of low LO performance in planar structures. We included a metasurface of single-square patterns in the monolayer to increase absorption from 60.12% to 65.15% in 1–20 GHz. Further, increasing LO performance is possible by laminating monolayer structures.

We optimized the laminated structures to provide effective EMI shielding and LO performance, finding an absorption increase of up to 75.45%. We compared monolayer and laminated design solutions for EMI shielding and LO features in the context of aviation transparencies. Planar layers on monolayer structures may not satisfy the application-specific requirement where thickness cannot be changed. In this case, instead of a planar layer, a patterned layer can achieve higher LO through absorption. On the other hand, laminated structures with planar layers achieve the highest absorption, but they come with drawbacks such as additional weights and a complex fabrication process that involves lamination of the layers.

Chapter 4 will discuss the relationship between the conductive film utilized in the RF numerical calculations and its effect on the optical performance.

Chapter 4

Optically Transparent Electromagnetic Interference Shielding of ZTO/Ag/ZTO

This chapter is based on our manuscript “Large-Area (50 cm × 50 cm) Optically Transparent Electromagnetic Interference (EMI) Shielding of ZTO/Ag/ZTO: An Analytical/Numerical and Experimental Study of Optoelectrical and EMI Shielding Properties ” by A. T. Astarlioglu et al., published (2024).

In Chapter 4, we extend the RF numerical calculations from Chapter 3 by incorporating the optical behavior of the architecture in the context of EMI shields. We defined thin-film coatings as resistive films and assumed that they were infinitely thin in the RF calculations in Chapter 3.

Chapter 4 covers the optical calculations in which the wavelength range becomes comparable to the thickness of the thin-film coatings in the nanometer range. Therefore, we studied the optical characteristics of the ZTO/Ag/ZTO (ZAZ) thin-film coatings, defining the thickness of each layer accordingly. Chapter 4

includes the large-area fabrication and characterization techniques, the electromagnetic and optical performance, and the structural performance of the ZAZ-coated PC optically transparent EMI shield.

4.1. Fabrication and Characterization

Section 4.1 explains the fabrication and characterization of the ZAZ coating on the PC substrate. We deposited ZAZ multilayers onto a 5.8 mm thick 50 cm x 50 cm PC substrate using direct-current magnetron sputtering from ZTO and Ag targets at room temperature. We used a ZTO target with a Zn: Sn atomic ratio of 2:1, which is thermodynamically stable, for the sputtering. The vacuum chamber was first evacuated to a base pressure of less than 5×10^{-6} Torr using a back and turbomolecular pump. We fixed the distance between the targets and substrate holder at 8 cm for the ZTO target and 10 cm for the Ag target. We set the sputtering power to 75 W for the ZTO target and 50 W for the Ag target, respectively. We pre-sputtered the surfaces of the ZTO and Ag targets in the argon (Ar) gas flow for 10 min before each deposition process to remove the native oxide layer.

Multilayer thin film coatings were achieved by scanning the magnetron sputtering gun with three-axis movement capability. Compared to conventional systems, the deposition system's distinguishing factor is the vacuum-compatible three-axis stepper motor connected to the 2-inch magnetron sputtering gun, as shown in Figure 4.1. The x - and y - axes were used for surface scanning, while the z -axis was utilized to set the distance between the target and sample surface. This configuration allows for the deposition of the thin film coatings within the high-vacuum environment, ensuring accurate positioning of the sputtering guns on the PC substrate.

We optimized the sputter gun along the x -, y -, and z - axes for both the Ag and ZTO targets to prevent overlapping or gaps to achieve uniform coating over large areas. The overlapping can cause excessive layer thickness, while the gap results in insufficient thickness, negatively affecting the designed structure's optical and electrical performance [96].

To create a large-area multilayer thin film coating, we used two sputtering guns. Primarily, we used the first scanning gun containing the ZTO target to grow the ZTO thin film. Next, we reserved the second scanning gun with the Ag target for depositing the Ag thin film. Lastly, the ZTO target scanned the sample surface to grow the final ZTO thin film, thereby terminating the stratified structure. The sputtering gun was moving at 400 cm/min for the ZTO target and 1,000 cm/min for the Ag target. The faster movement of the Ag target is due to the higher sputtering yield compared to the ZTO target, which results in faster film deposition [97].

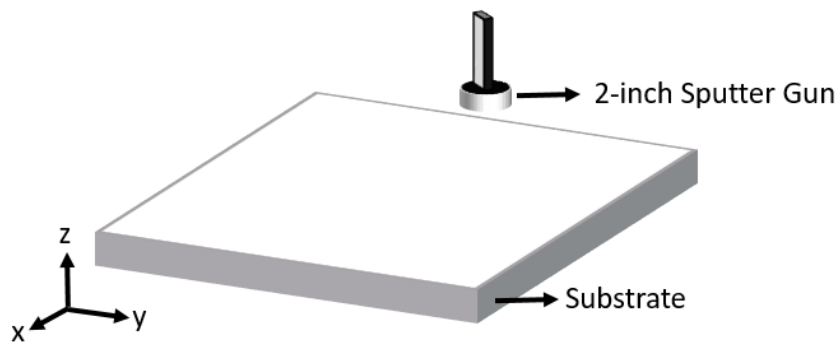


Figure 4.1. Schematic of the 2-inch scanning magnetron gun connected to a vacuum-compatible three-axis stepper motor, used for achieving uniform coating over large areas.

The optical properties of multilayer films were investigated by optical transmittance measurements in the range of 400–2,500 nm using an Agilent Cary 5000 UV-Vis-NIR spectrophotometer. Sheet resistances of the sample were

measured and mapped using a Hall effect measurement system (NanoMagnetics Instruments-ezHEMs) in $I - V$ mode.

We conducted electromagnetic characterization of the sample using a free-space focused-beam system (Compass Technology, USA) in the 2–20 GHz frequency range. The EMI shielding effectiveness in dB was obtained using:

$$SE = 20 \log \left| \frac{E_{in}}{E_t} \right| \quad (4.1)$$

where E_{in} and E_t represent the electric field strengths of incident and transmitted electromagnetic waves, respectively [98]. The EMI performance of the ZAZ–PC was numerically calculated using CST Microwave Studio utilizing a unit cell module in 2–20 GHz, as discussed in Chapter 3.

We determined the thickness of each layer using field emission scanning electron microscopy (FESEM, Carl Zeiss) and high-resolution transmission electron microscopy (HRTEM, Jeol) after etching with focused ion beam (FIB, Nova 600i Nanolab) lithography. The surface roughness of ZAZ on PC was observed under non-contact mode to minimize the surface damage using atomic force microscopy (AFM, Park System XE-100). AFM data was analyzed using the Gwydion software. In addition, the surface roughness was measured according to the JIS B0601:2001 standard by laser scanning confocal microscope (Keyence VKX-100). Secondary ion mass spectroscopy (SIMS, Hiden Analytica) was employed using an oxygen gun with an emission of 10 mA and 4 kV ion energy to analyze diffusion between thin film layers. Grazing incidence X-ray diffraction (GIXRD, PANalytical) was conducted in an X-ray diffractometer, with Cu-K α radiation ($\lambda=1.5406 \text{ \AA}$) and at a grazing angle of 0.75° between $2\theta = 20 - 70^\circ$ with a step size of 0.08° for determining crystal structure of ZAZ–PC.

We used the transfer matrix method (TMM) [99] to analytically calculate the transmission and reflection of the structure. The optical constants of each layer of the transparent EMI shield, including PC, ZTO, and Ag, were obtained using the VASE ellipsometer (J.A. Woollam, USA), given in Figure 4.2, and utilized in the TMM calculations.

The refractive index of Ag is lower than the ZTO and PC, indicating its superior reflectivity, while its extinction coefficient is higher below 414 nm and beyond 487 nm. The Ag layer has a lower extinction coefficient in 414–487 nm because its plasma frequency falls into the visible region at the nanometer level [100]. In this 414–487 nm wavelength range, the Ag layer absorbs less, allowing visible-light transmission. In contrast, ZTO and PC layers exhibit a stable and relatively high refractive index (depicted in Figure 4.2a) with negligible extinction coefficient (depicted in Figure 4.2b), positioning them as a suitable option for optical substrates that demand high optical transparency.

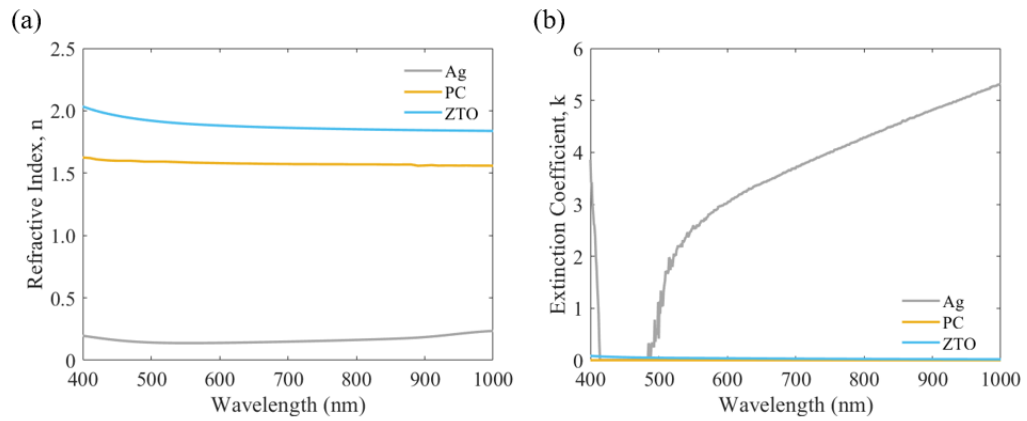


Figure 4.2. (a) Refractive index n and (b) extinction coefficient k of PC substrate, ZTO film, and Ag film in 400–1000 nm.

4.2. Electromagnetic Interference Shielding Performance

In Section 4.2, we first determined the required thickness of the metal layer corresponding to the sheet resistance value of $10 \Omega/\text{sq}$ in the optically transparent EMI structure to provide over 99% EMI shielding, which was discussed in Chapter 3. The contribution of ZTO layers was neglected in determining the EMI shielding performance due to high sheet resistance value of amorphous ZTO [69].

Before including the bottom and top ZTO layers' thicknesses, the metal thickness was determined to be 18 nm to achieve a sheet resistance value of $10 \Omega/\text{sq}$. We measured the sheet resistance of the coating from 25 zones of ZAZ-PC to validate uniformity along the surface. The results indicate an average sheet resistance of $10.28 \Omega/\text{sq}$ with a deviation of $0.63 \Omega/\text{sq}$. Figure 4.3a represents the measured sheet resistance values, whereas Figure 4.3b shows the different regions on $50 \text{ cm} \times 50 \text{ cm}$ ZAZ-PC where the measurements were taken.

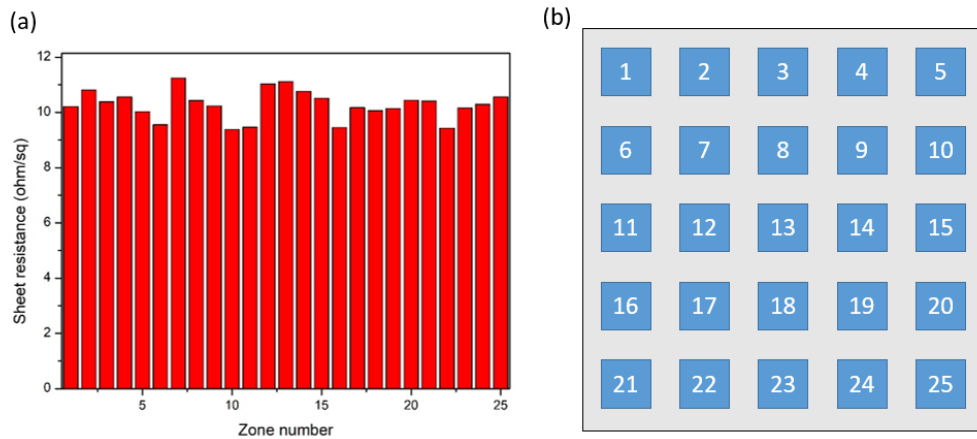


Figure 4.3. Sheet resistance measurements from different zones of ZAZ-PC along with (b) zone number mapping on the $50 \text{ cm} \times 50 \text{ cm}$ surface.

The free-space configuration for the experimental measurements and numerical calculations to evaluate EMI shielding performance is shown in Figures 4.4a and b, respectively. We utilized the unit cell module to numerically determine the transmission loss of the ZAZ-PC structure along the frequency range of 2–20 GHz. The electromagnetic wave propagates in the z-direction while the structure is periodic in x - and y -directions.

We calculated shielding effectiveness using (4.1) and presented its relation between the sheet resistance (in Ω/sq) and the transmission (T%) for varying sheet resistance values of the resistive film on 5.8 mm thick PC, as presented in Figure 4.4c. The shielding effectiveness decreases as the sheet resistance value of the structure increases. This means that the structure transmits more portion of the electromagnetic wave impinging on it and cannot satisfy an effective EMI shielding.

The shielding effectiveness of the ZAZ-PC structure was numerically and experimentally found to be 27.43 and 27.73 dB, respectively, as shown in Figure 4.4d. In other words, experimental and numerical results show that over 99% of the incoming electromagnetic wave was shielded along the 2–20 GHz frequency range.

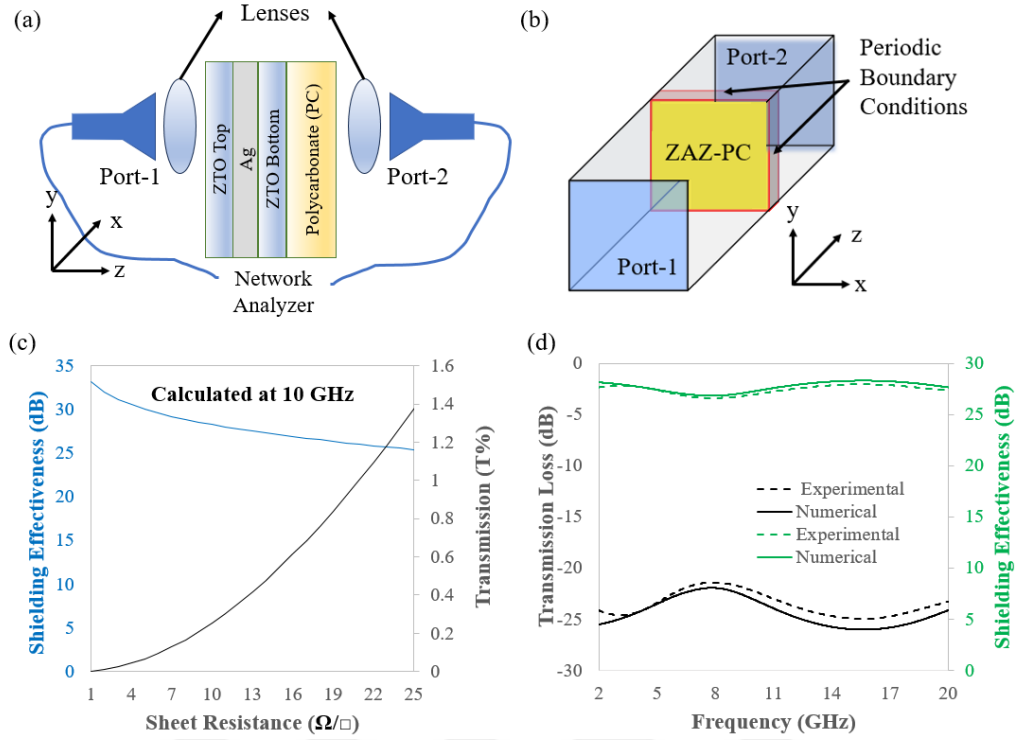


Figure 4.4. (a) Free-space system used for experimental measurements, including a network analyzer connected to Port – 1 and Port – 2 and lenses to focus electromagnetic waves. The ZAZ-PC under test is placed between the ports. (b) Schematic of the unit cell module, (c) sheet resistance dependent transmission loss (dB) and transmission (T%), and (d) experimentally measured and numerically computed transmission loss and shielding effectiveness of the ZAZ stratified structure on 5.8 mm thick PC over 50 cm $\times$ 50 cm area.

In Figure 4.5, we calculated the electric field intensity at 10 GHz, where EM waves propagating in the z-direction. In Figure 4.5a, some portion of the EM waves can pass through the PC. On the other hand, in Figure 4.5b, EM waves cannot pass through the other side of the ZAZ-PC structure thanks to the high EMI shielding performance.

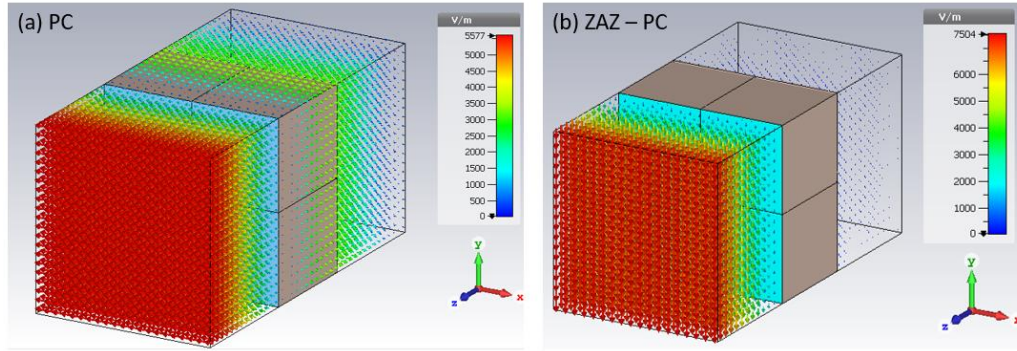


Figure 4.5. Numerically calculated electric field intensity mapping of (a) the PC alone and (b) the ZAZ-PC structures at 10 GHz.

The EMI shielding mechanism was studied for both PC and PC-ZAZ in terms of transmission, reflection and absorption across 2–20 GHz, as shown in Figure 4.6. The numerical results indicate that the primary mechanism of EMI shielding involves the reflection of the EM waves through the mobile charge carriers in the metal Ag layer incorporated with the secondary mechanism of absorption by the electric dipole [57].

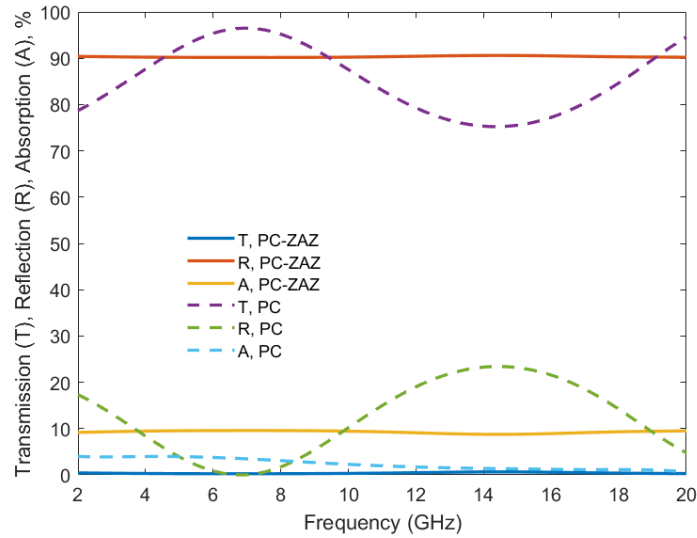


Figure 4.6. Numerically calculated transmission (T%), reflection (R%) and absorption (A%) of PC and ZAZ-PC structures across 2 - 20 GHz.

4.3. Optical Performance

We present the optical characteristics of the transparent EMI shield to evaluate optical clarity, night-vision applications, and solar irradiation protection in Section 4.3. To do so, we used the transfer matrix method (TMM) in our analytical calculations. The TMM considers multiple reflections of a multilayer structure and computes the structure's optical transmission, reflection, and absorption in multilayers, as shown in Figure 4.7a.

In Section 4.2, we determined the thickness of the metal layer to be 18 nm, resulting in a $10 \Omega / \text{sq}$ to satisfy over 99% EMI shielding. Next, we optimized the thickness values of the bottom and top ZTO layers in the PC-ZAZ structure for the highest transmission in 400–700 nm, as shown in Figure 4.7b. All layers in the structure were assumed to be infinite in the x - and y -directions for the TMM calculations. Calculated average transmission, reflection, and absorption in the visible region of 400–700 nm, where the ZTO top and bottom layers were swept between 0–60 nm, are shown in Figures 4.8a, b, and c respectively.

The optical loss due to the ZAZ coating lies below 15% in the elliptical region marked with dashed line in Figure 4.8a. These calculations highlight the significance of thickness management in multilayer coatings for obtaining the desired optical characteristics. Since in our study we desire to obtain high optical clarity, the thickness values were determined for the lowest optical loss. For the highest transmission, the thickness of each ZTO layer of the ZAZ–PC structure was determined to be *ZTO bottom* (20 nm)/Ag (18 nm)/*ZTO top* 40 (nm) based on the analytical calculations.

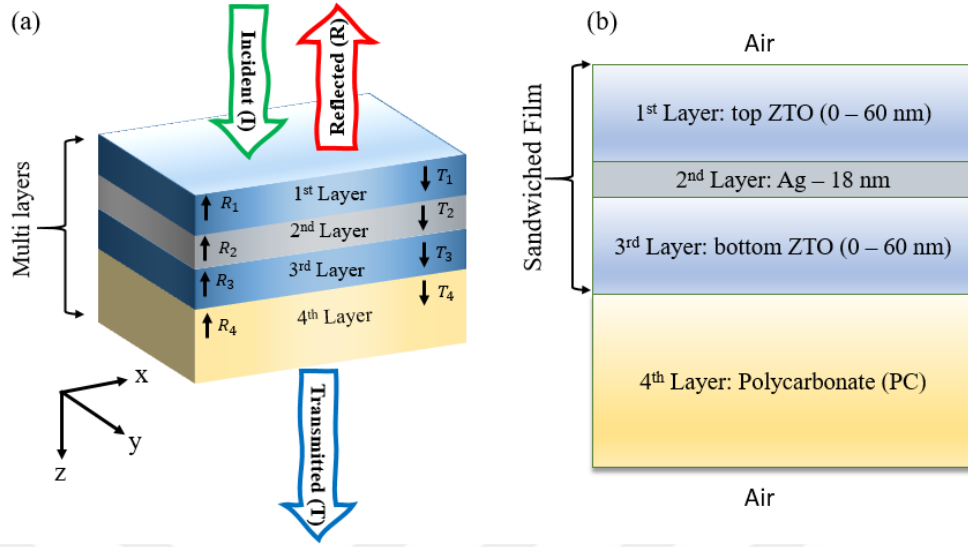


Figure 4.7. (a) Schematic illustration of interactions between multilayers; Incident (I) = Reflected (R) + Transmitted (T) + Absorbed (A). $T=T_1+T_2+T_3+T_4$ and $R=R_1+R_2+R_3+R_4$. (b) The schematic diagram depicts the structure used in the analytical calculations, consisting of a sandwiched film on a 5.8 mm PC substrate. In the sandwiched film, the Ag layer thickness was fixed to 18 nm, and *top* ZTO and *bottom* ZTO layers were swept between 0 and 60 nm.

The absorption rises when the *bottom* ZTO film thickness is between 20 and 60 nm and the *top* ZTO thickness is between 0 and 20 nm, as shown in Figure 4.8c. When the *bottom* ZTO thickness is between 0 and 20 nm and the *top* ZTO thickness is between 0 and 60 nm, the absorption drops.

Decreasing the thickness of the *top* ZTO layer in the sandwiched film can cause more visible light to pass through and interact with the Ag layer. Since the Ag layer is absorptive in the visible region but not near its plasma frequency, the average absorption increases in the range of 400–700 nm. A thicker *top* ZTO layer makes reflection better and decreases absorption. Thickening the *top* ZTO layer improves results in constructive interferences and enhance visible light transmission. Therefore, anti-reflective feature of the *top* ZTO layer works as an anti-reflective coating, reducing the Ag layer's absorption.

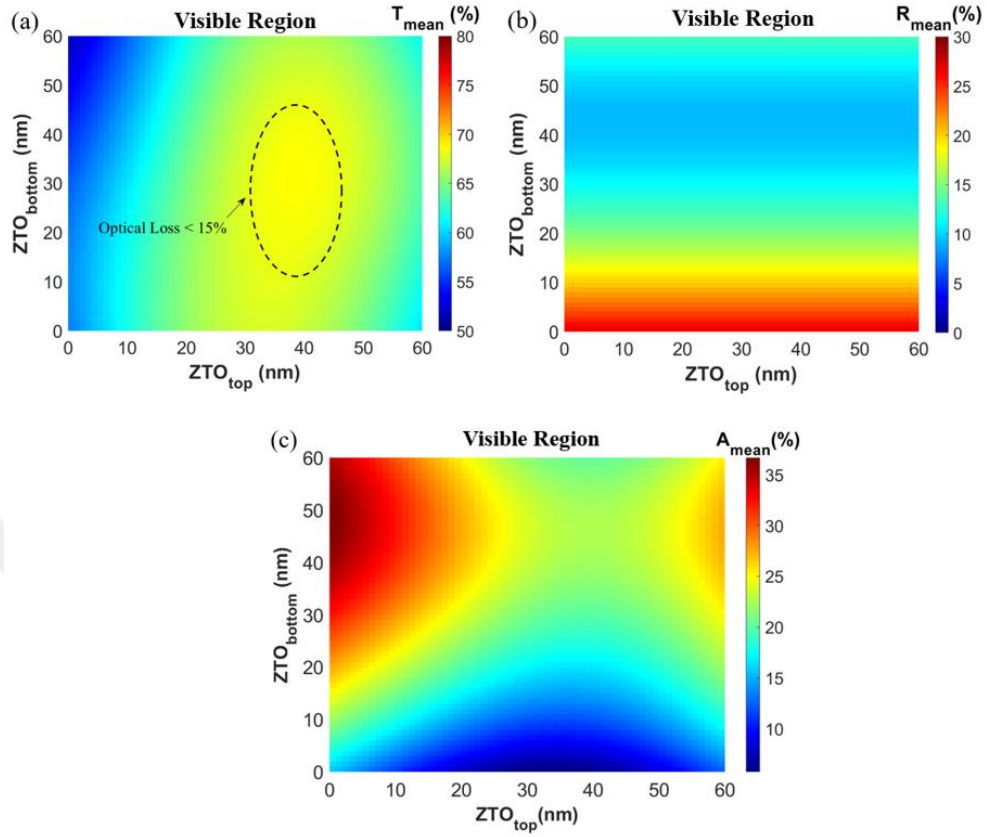


Figure 4.8. (a) Calculated average transmission T_{mean} in 400–700 nm, (b) calculated average reflection R_{mean} in 400–700 nm, and (c) calculated average absorption for the PC – ZTO *bottom*/Ag (18 nm)/ZTO *top* structure on 5.8 nm thick PC while varying film thicknesses of the *top* and *bottom* ZTO layers.

For comparison purposes, we used indium tin oxide (ITO) as a substitute for ZTO in the ZAZ structure, given its widespread use in optoelectronics, as discussed in Chapter 2. We sandwiched the 18 nm thick Ag layer between ITO layers to compare the optical characteristics. Park et. al. [101] deposited ITO at room temperature and found that the electrical properties of the Ag layer, which has a higher level of electrical conductivity than the ZTO, determine the sheet resistance of the ITO/Ag/ITO multilayer. Besides, these stratified structures, sandwiching an electrically conductive layer between poorly conductive layers, tend to increase the carrier concentration. However, the carrier mobility decreases compared to single-layer configurations due to the formation of interfacial scattering sites [102]. This also limits the electrical conductivity even if the

thickness of the conductive layer increases since the electrical conductivity increases with the carrier mobility and carrier concentration [57].

In our calculations, we used the refractive index and extinction coefficient of the ITO fabricated by Ozyuzer et. al. [57]. As shown in Figure 4.9a, we calculated the highest average transmission in 400–700 nm to be 68.16%, with the *bottom* ITO film thickness of 32 nm and the *top* ITO thickness of 35 nm. Therefore, we showed that the ZTO leads to slightly higher optical transmission than the case of using ITO and is a suitable candidate to replace it, as discussed in Chapter 2.

Figures 4.9b and c show the average reflection and absorption in 400–700 nm with varying bottom and top ITO thicknesses (0–60 nm). In Figure 4.9b, for which the *top* ITO thickness is tuned between 25–50 nm and the *bottom* ITO between 20–60 nm, we calculated the average reflection is below 10% while the average absorption is above 25%. In the same region, the structure's optical loss is approximately 15%, and its optical transmission is comparable to that of the ZAZ multilayer on the 5.8 mm thick PC.

For the same thickness values, the ITO/Ag/ITO multilayer yields stronger absorption and weaker reflection than the ZTO/Ag/ZTO multilayer. This is because ITO has a higher extinction coefficient than ZTO. Depositing an ITO film at an elevated temperature of 450°C can enhance optical transmission in the 400–700 nm range by improving crystallinity and reducing defects, resulting in a decrease in the extinction coefficient [57]. Since our substrate is PC and has a glass transition temperature around 138°C [103], it cannot withstand temperatures required for high-quality ITO films. For the aforementioned reasons, we focus on the ZTO/Ag/ZTO structure in this thesis work.

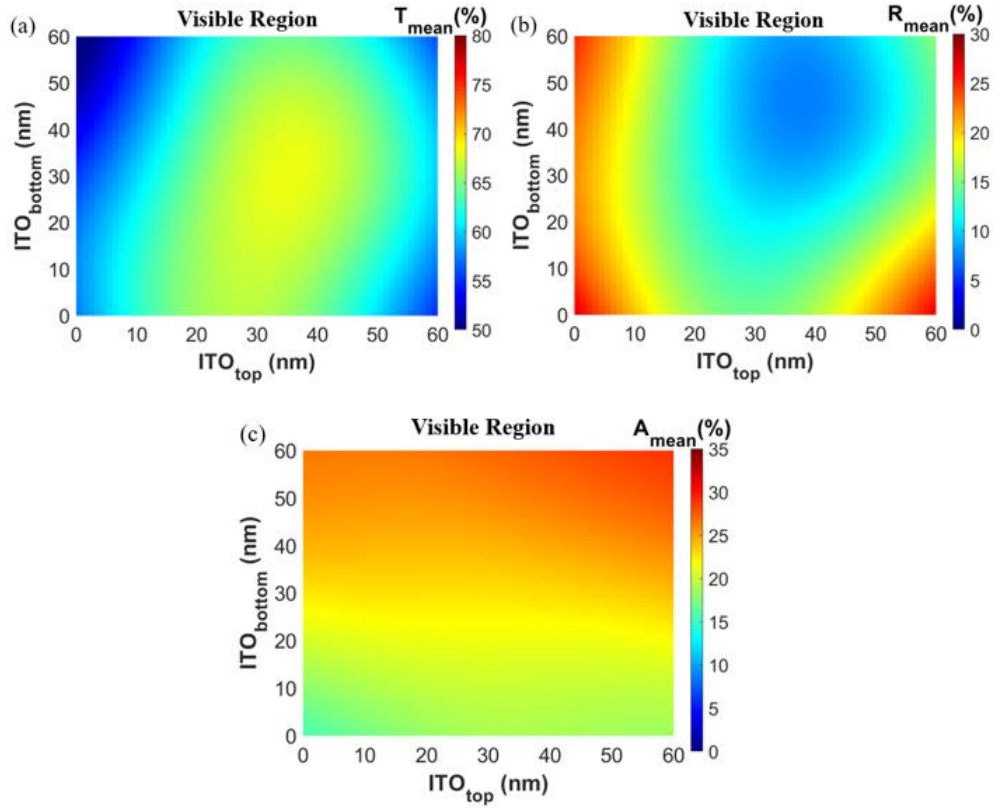


Figure 4.9. (a) Calculated average transmission T_{mean} in 400–700 nm, (b) calculated average reflection R_{mean} in 400–700 nm, and (c) calculated average absorption in 400–700 nm for the PC – ITO *bottom*/Ag (18 nm)/ ITO *top* structure on 5.8 mm thick PC while varying film thicknesses of the top and bottom ITO layers.

Next, we investigated the transmission, reflection and absorption of the ZAZ multilayer in the visible region when the thickness of Ag layer is not fixed and varied between 0–25 nm, as depicted in Figures 4.10a, b and c, respectively. The top and bottom ZTO layers are symmetric and their thickness is equal.

To increase EMI shielding performance, we need to increase the thickness of Ag layer further. When we increased the thickness of the Ag layer from 18 to 20 nm, the average transmission in the visible region becomes 66.37%, meaning that optical loss increases by 1.97%. On the other hand, decreasing the Ag layer

thickness from 18 to 16 nm, the transmission in the visible region was calculated 70.50%, meaning that the optical transmission enhancement is by 2.16%.

The thinner 16 nm Ag layer satisfies the EMI shielding about 99% and achieves higher optical transparency. However, considering practical constraints, such as the scanning speed of the sputtering gun over large areas, we prefer to maintain an 18 nm thickness profile. In symmetric ZTO layer configuration, the reflection was found to have diminishing effect on the transmission while the primary factor decreasing the transmission was the increased absorption.

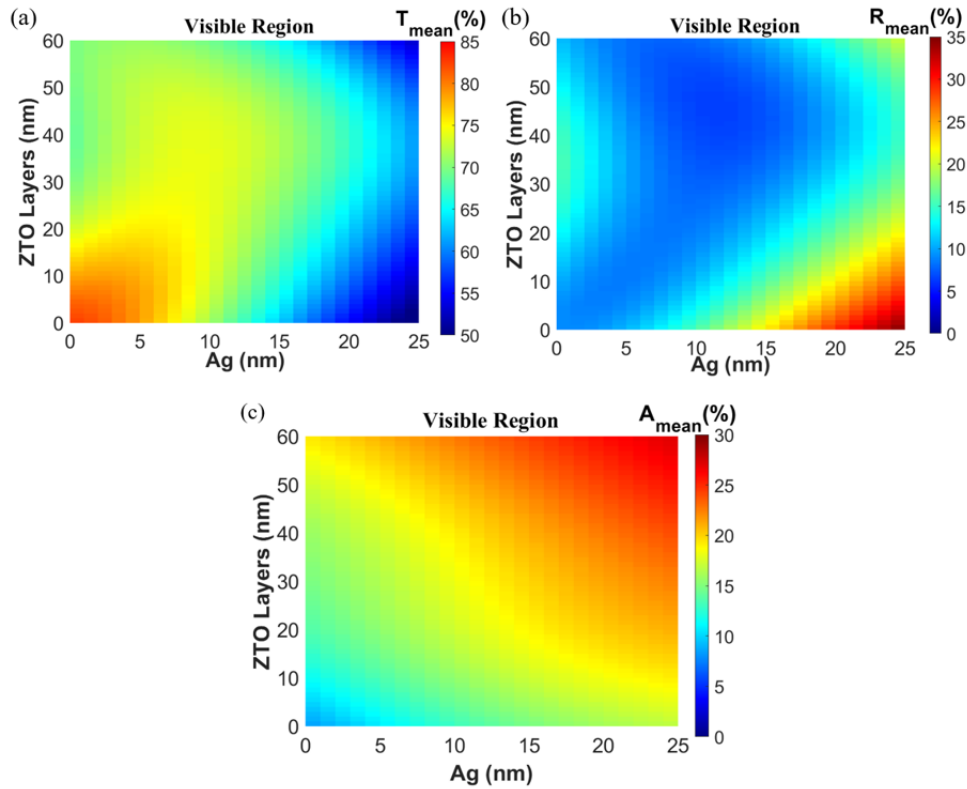


Figure 4.10. (a) Calculated average transmission T_{mean} in 400–700 nm, (b) calculated average reflection R_{mean} in 400–700 nm, and (c) calculated average absorption A_{mean} in 400–700 nm for the PC – ZTO *bottom*/Ag/ZTO *top* structure on 5.8 mm thick PC. The top and bottom ZTO layers are identical.

Similarly, we investigated the transmission, reflection and absorption of the ZAZ multilayer in the near-infrared region, as shown in Figures 4.11a, b, and c, respectively. Unlike visible region, the increase in the Ag thickness dramatically decreases the average transmission due to increased reflection, as shown in Figure 4.11b. The effective reflection of Ag layer in near-infrared region arises from its high density of free electrons, minimal absorption due to low interband transitions, and excellent electrical conductivity [104], [105]. These optical properties of Ag enables efficient reflection and minimizes optical losses in 700–1000 nm. Our findings show that the average absorption (depicted in Figure 4.11c) does not vary much as the Ag layer thickness increases compared to the reflection and transmission.

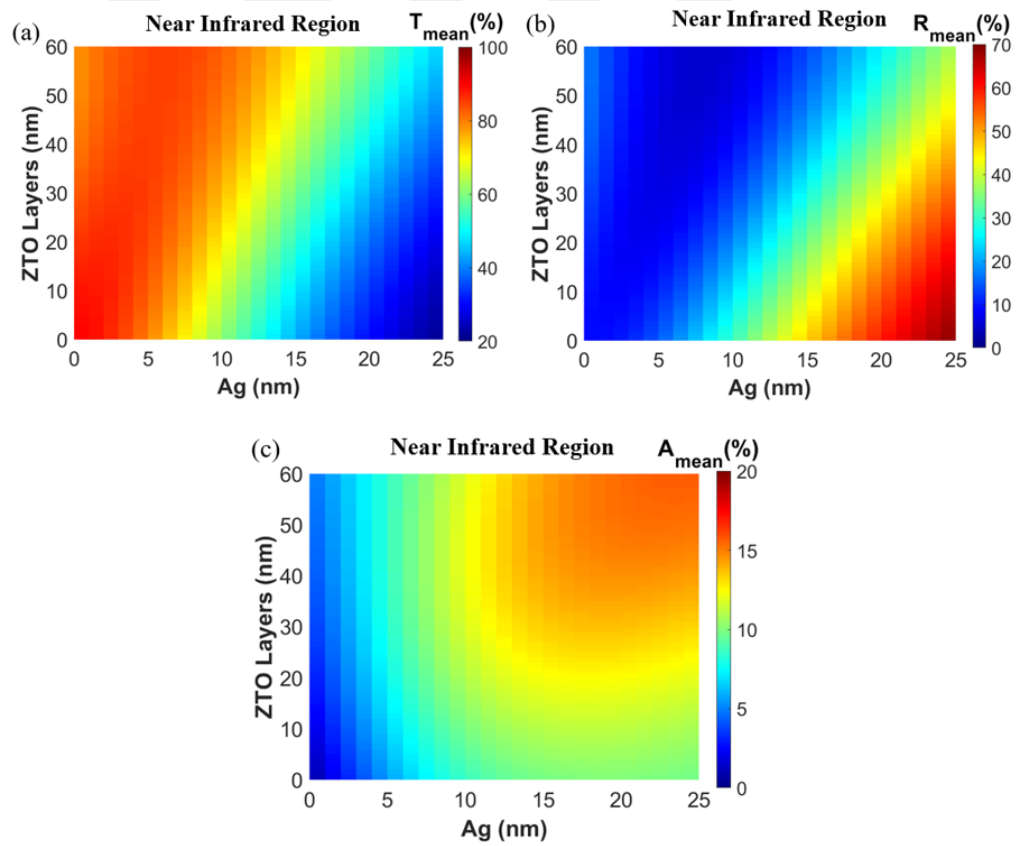


Figure 4.11. (a) Calculated average transmission T_{mean} in 700–1000 nm, (b) calculated average reflection R_{mean} in 700–1000 nm, and (c) calculated average

absorption A_{mean} in 700–1000 nm for the PC – ZTO bottom/Ag /ZTO top structure on 5.8 mm thick PC. The top and bottom ZTO layers are identical.

The spectral behavior of the PC with and without a ZAZ coating in 400–700 nm and 700–1000 nm ranges are shown in Figures 4.12a and b, respectively. Analytical and experimental results are consistent in the spectral ranges of both visible and near-infrared regions. Across the 400–1000 nm wavelength range, this agreement validates the accuracy of optical constants obtained through the ellipsometer, which was then used in our analytical calculations.

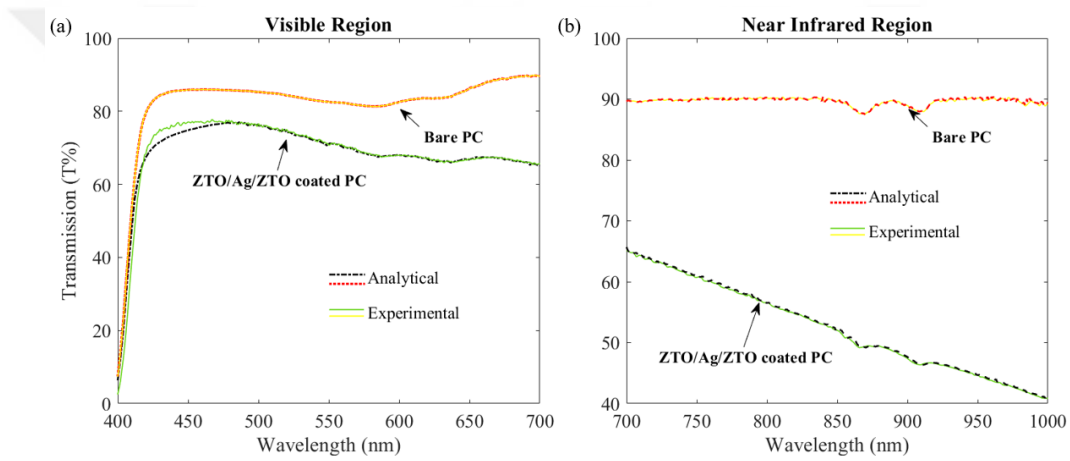


Figure 4.12. Spectral transmission of the ZAZ–PC structure with and without a coating in the (a) visible (400–700 nm) and (b) near-infrared (700–1000 nm) regions.

The average transmission values of the bare PC and ZAZ–PC are listed in Table 4.1 for comparison purposes. In the visible region, the analytical transmission results of PC and ZAZ–PC were found to be 82.23% and 68.34% whereas the experimental results were 82.31% and 68.80%, respectively.

Table 4.1. Average analytical and experimental transmission (T%) of the bare PC and ZAZ-PC in the visible (400–700 nm) and the near-infrared (700–1000 nm) regions.

	Bare PC (T%)		ZAZ-PC (T%)	
	Analytical	Experimental	Analytical	Experimental
Visible Region (400–700 nm)	82.23	82.31	68.34	68.80
Near Infrared Region (700–1000 nm)	89.65	89.67	52.49	52.49

The coating with the highest transmission in 400–700 nm was applied to the PC substrate with different thickness values to investigate the optical loss caused by the substrate thickness. The schematic of the ZAZ-coated PC used in the analytical calculations and calculated spectral transmission are presented in Figures 4.13a and b, respectively. The average transmission of the ZAZ-PC structure decreases as the PC thickness increases, with the corresponding values of 73.09%, 68.34%, 64.86%, 61.16%, and 57.81% for thicknesses of 1 mm, 5.8 mm, 10 mm, 15 mm, and 20 mm, respectively, in accordance with the Beer-Lambert law.

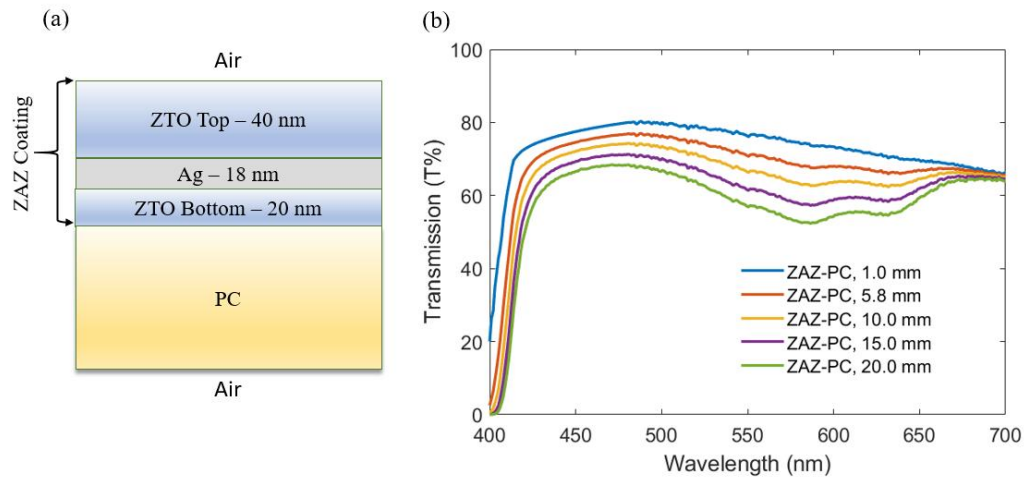


Figure 4.13. Schematic of the ZTO *bottom* (20 nm)/Ag (18 nm)/ZTO *top* 40 (nm) coated PC (a), and calculated spectral transmission in 400–700 nm for various PC thickness values of 1.0 mm, 5.8 mm, 10.0 mm, 15.0 mm, and 20.0 mm.

Next, we studied ZTO *bottom*/Ag (ZA), Ag/ZTO *top* (AZ), and ZAZ multilayer coatings to investigate the optical performance contribution of each layer in the coating. The optical transmission of the Ag, ZA, AZ, ZAZ on the PC in 400–700 nm, is given in Figure 4.14c. The Ag layer without ZTO layers shows the highest transmission below 500 nm, but the sharp decrease above 500 nm reduces the average transmission by 58.14%. The addition of a ZTO layer to the Ag layer below, as depicted in Figure 4.14a, AZ coating, results in a reduction in transmission below 500 nm and an increase above; however, the average transmission remains relatively low compared to the ZAZ coating. Including a ZTO layer at the top of the Ag layer, as presented in Figure 4.14b, significantly boosts the transmission to 67.70% by reducing the reflection resulting from refractive index mismatch. Still, further increasing the average optical transmission is possible with the symmetric placement of the ZTO layers.

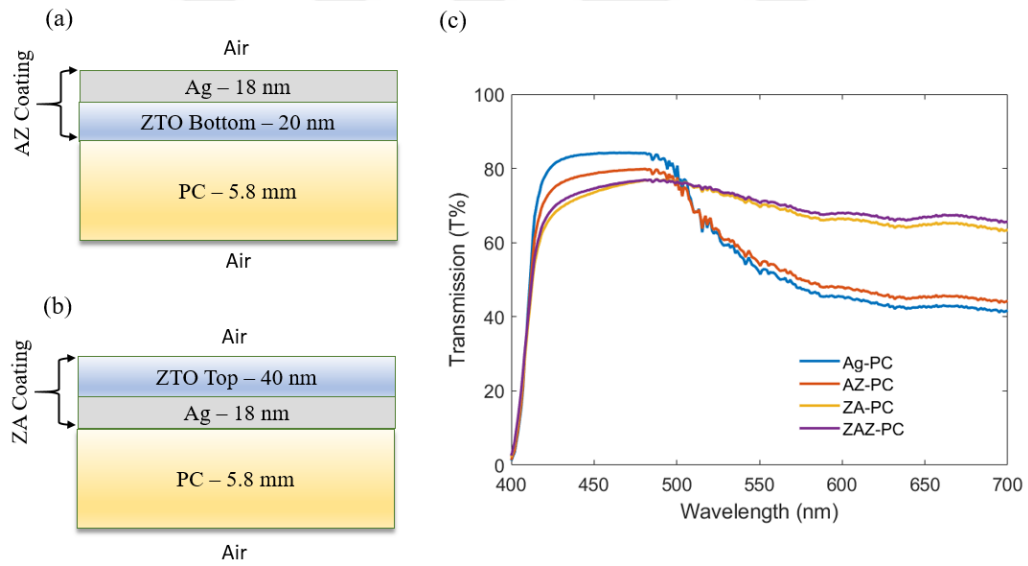


Figure 4.14. Schematic of the ZTO *bottom* (20 nm)/Ag (18 nm) (a) and Ag (18 nm)/ZTO *top* (40 nm) (b) coatings on 5.8 mm PC and (c) the calculated spectral transmission in 400–700 nm for Ag, ZTO *top*, ZTO *bottom* and ZAZ coatings.

We spectrally limited our optical performance studies to the visible region (400–700 nm) of the electromagnetic spectrum. We extended our spectrum of interest

to 700–1000 nm for night-vision applications. Conventional night-vision systems work at a specific wavelength, while more advanced night-vision systems utilize multi-spectral signals, and average transmission provides comprehensive imaging [106]. Therefore, the average transmission and reflection of ZAZ–PC were calculated in the near-infrared region of 700–1000 nm and compared with the experimental results, presented in Figures 4.15c and d, respectively. Remarkably, the ZTO top layer affects optical transmission and reflection more than the ZTO bottom layer in the near-infrared region. Depending on night vision requirements, the transmission and reflection of the stratified structure can be adjusted by tuning the film thicknesses of ZTO layers while slightly changing the transmission in the visible region when the metal layer thickness is fixed.

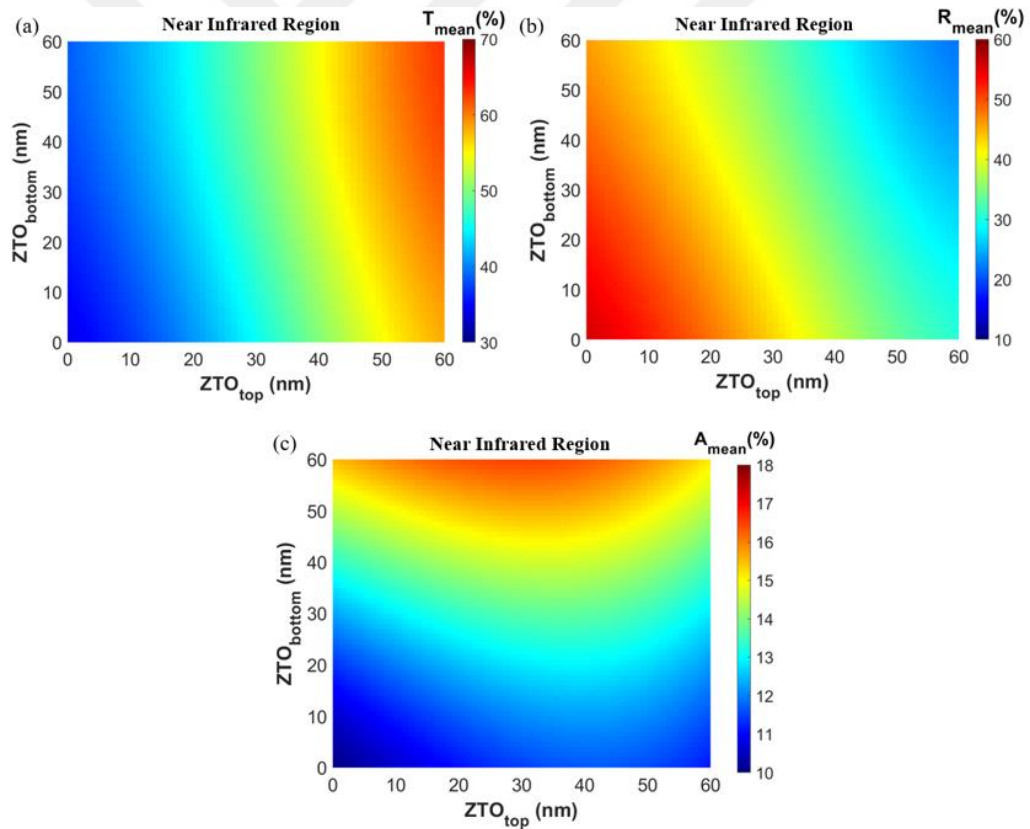


Figure 4.15. Calculated average transmission (a), reflection (b), and absorption (c) of the ZTO *top*/Ag (18 nm)/ZTO *bottom* structure on the 5.8 mm thick PC in the near-infrared for night-vision applications.

Next, we extended the wavelength range up to 2.5 μm to further investigate the impact of solar irradiation. Solar irradiance is effective in the spectral regions of ultraviolet (UV), visible, and NIR over a wide wavelength range of 280–2500 nm. Solar irradiance beyond 2.5 μm is negligible, as illustrated in Figure 4.16. Therefore, it is not included in the calculations.

Solar irradiance is the amount of solar energy per unit area received from the sun's radiation, measured in Watts per square meter (W/m^2). Figure 4.16 provides the solar irradiance per unit wavelength interval at a given wavelength $\text{Wm}^{-2}\text{nm}^{-1}$ from the sun in the Earth's atmosphere. Therefore, we analytically calculated the reflection, transmission, and absorption of the ZAZ-PC. Subsequently, we calculated the reflected, transmitted, and absorbed solar irradiance by the ZAZ-PC structure.

The total solar irradiance that reaches the Earth's surface is $1,000 \text{ W}/\text{m}^2$ according to the ASTM G173–03. The visible region, ranging from 380 to 780 nm, exhibits the highest solar irradiance of $549 \text{ W}/\text{m}^2$, accounting for more than half of the total irradiance. The UV region, 280–380 nm, has the smallest contribution, at $66 \text{ W}/\text{m}^2$, which aligns with the fact that much of the UV radiation is absorbed by the Earth's atmosphere, particularly by the ozone layer [107]. Although UV radiation can deteriorate aviation transparency and poses a risk to pilot health, the canopy material's design aims to reduce these risks using UV-absorption materials [108]–[110].

The infrared region of the solar irradiance is more dominant in heating objects because it has longer wavelengths that are more effective at transferring energy to molecules, causing them to vibrate and generate heat [111]. Therefore, we focused on the infrared region rather than UV and visible in the context of solar irradiation protection, as it is critical for thermal management.

NIR, spanning 780–3000 nm, with an irradiance of 389 W/m², emphasizes the substantial portion of solar irradiation that primarily contributes to heat. The solar irradiance is 7 W/m² between 2000–4000 nm and has a negligible contribution. Therefore, the wavelength range of 780–2000 nm was selected in our thermal calculations, corresponding to the total solar irradiance of 383 W/m².

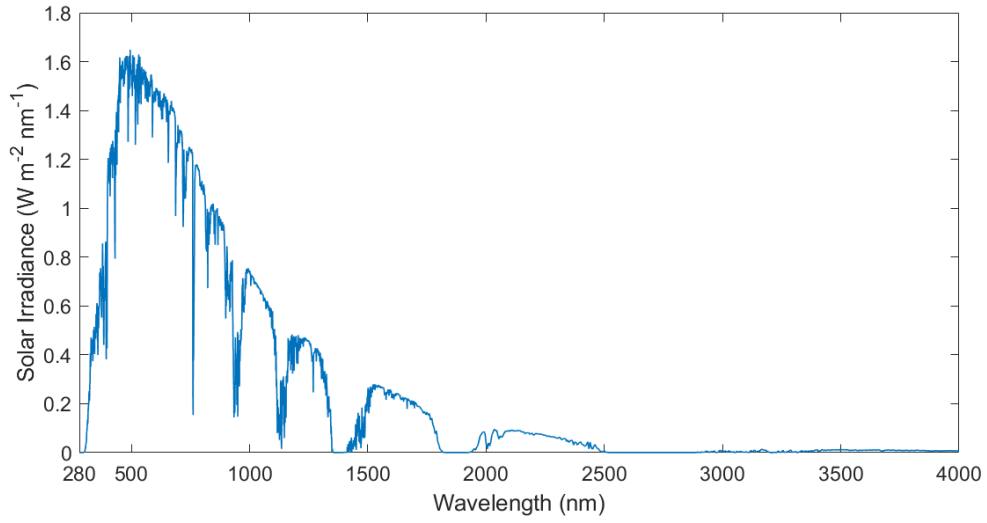


Figure 4.16. Spectral solar irradiance in the wavelength range of 280–4000 nm according to the ASTM G173–03.

We computed the total solar irradiation transmitted, reflected, and absorbed through the ZAZ-PC by the following relations:

$$I_{Transmitted} = \int_{\lambda_1}^{\lambda_2} I_{Solar}(\lambda)T(\lambda)d\lambda \quad (4.1)$$

$$I_{Reflected} = \int_{\lambda_1}^{\lambda_2} I_{Solar}(\lambda)R(\lambda)d\lambda \quad (4.2)$$

$$I_{Absorbed} = \int_{\lambda_1}^{\lambda_2} I_{Solar}(\lambda)A(\lambda)d\lambda \quad (4.3)$$

where $I_{Solar}(\lambda)$ is the solar irradiance at wavelength λ . $T(\lambda)$, $R(\lambda)$, and $A(\lambda)$ are the ZAZ-PC's transmittance, reflectance, and absorbance at wavelength λ . λ_1 and λ_2 define the wavelength range. The wavelength range was chosen as $\lambda_1 = 780 \text{ nm}$ – $\lambda_2 = 2000 \text{ nm}$.

Figures 4.17a, 4.18a, and 4.19a present the transmittance, reflectance, and absorbance of the uncoated PC, PC-ZAZ, and ZAZ-PC in the 780–2000 nm range, respectively. In the 780–2000 nm range, Table 4.2 provides the average transmittance, reflectance, and absorbance of PC without coating, PC-ZAZ, and ZAZ-PC. We applied the ZAZ coating to the outer surface of the ZAZ-PC, which directly faces solar radiation. On the other hand, the PC-ZAZ configuration applies the ZAZ coating to the inner surface.

The solar irradiance transmitted, reflected, and absorbed through PC, PC-ZAZ, and ZAZ-PC was calculated using (4.1)-(4.3), as shown in Figures 4.17b, 4.18b, and 4.19b and summarized in Table 4.3. The 5.8 mm thick PC without thin-film coating exhibits an average transmittance of 0.74, reflectance of 0.08, and absorbance of 0.18, corresponding to the calculated solar irradiance values of 315.81 W/m², 33.62 W/m², and 33.59 W/m², respectively. However, when ZAZ thin-film coating was applied to the PC's interior and exterior sides, the solar transmitted irradiance was reduced to 135.22 W/m² for both configurations. The position of the ZAZ at the interior or exterior does not affect the transmittance of the structure. However, it changes reflectance and absorbance, as summarized in Tables 4.2 and 4.3, respectively.

For the exterior thin-film coating, the ZAZ-PC structure reflects 223.11 W/m² of solar irradiance, compared to the interior thin-film coating of the PC-ZAZ structure 152.57 W/m². Tables 4.2 and 4.3 indicate that the ZAZ coatings lower the absorbance when applied to the structure's exterior while increasing the absorbance when applied to the interior. The decrease in absorption when the

ZAZ coating is applied to the exterior is due to the solar irradiation passing through the structure absorbed. Then, some portion is transmitted and partially reflected. The partially reflected solar irradiation travels through the PC and is absorbed again, causing in total higher absorption. On the other hand, the highest fraction of the solar irradiation reflected through the exterior ZAZ for the ZAZ-PC resulted in reduced absorbance.

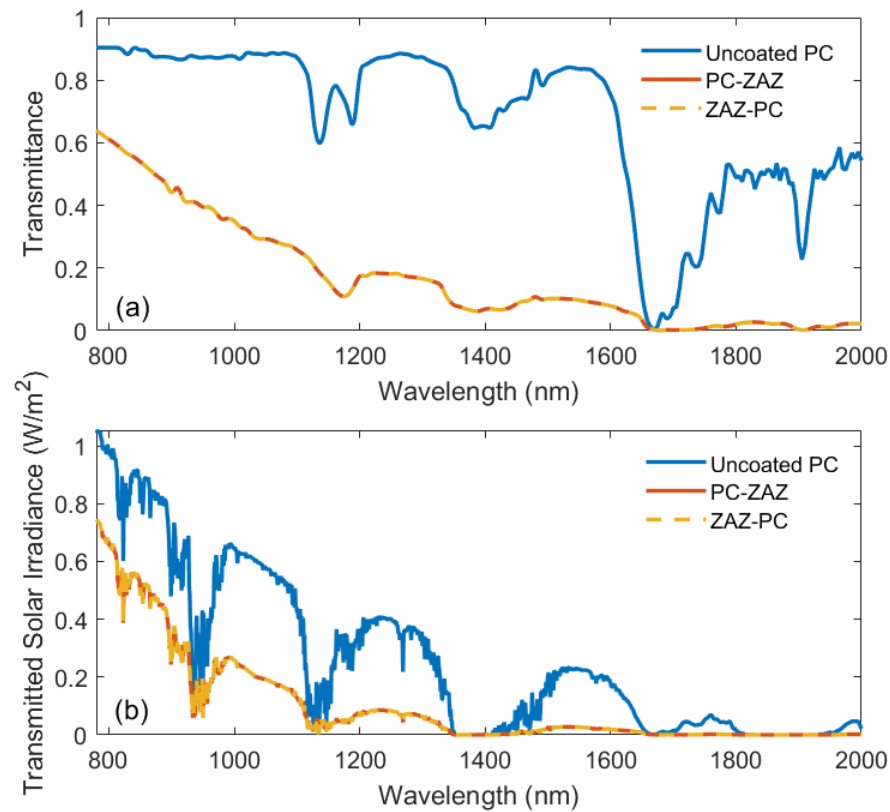


Figure 4.17. (a) Transmittance spectra and (b) transmitted solar irradiance as a function of the wavelength (780–2000 nm) for the PC and ZAZ-PC coatings. The top panel presents transmission percentage, while the bottom one shows transmitted solar irradiance in W/m^2 .

Solar irradiance transmitted through aviation transparent structures such as windshields, canopies and windows affects the temperature of the interior side [112]. The higher the transmitted solar irradiance through these transparencies, the more energy enters, leading to greater total absorption by internal surfaces

and resulting in a raised temperature due to the heating. The dissipated heat then increases the temperature of the cockpit, especially in sun-lit environments, resulting in uncomfortable conditions for the pilots and degrading equipment inside the cockpit over time [113]. This relationship between solar irradiance, the aviation transparent structures' optical response, and interior side temperature is crucial for designing canopies that improve pilot or passenger comfort and safety by minimizing heat buildup during ground operations [114].

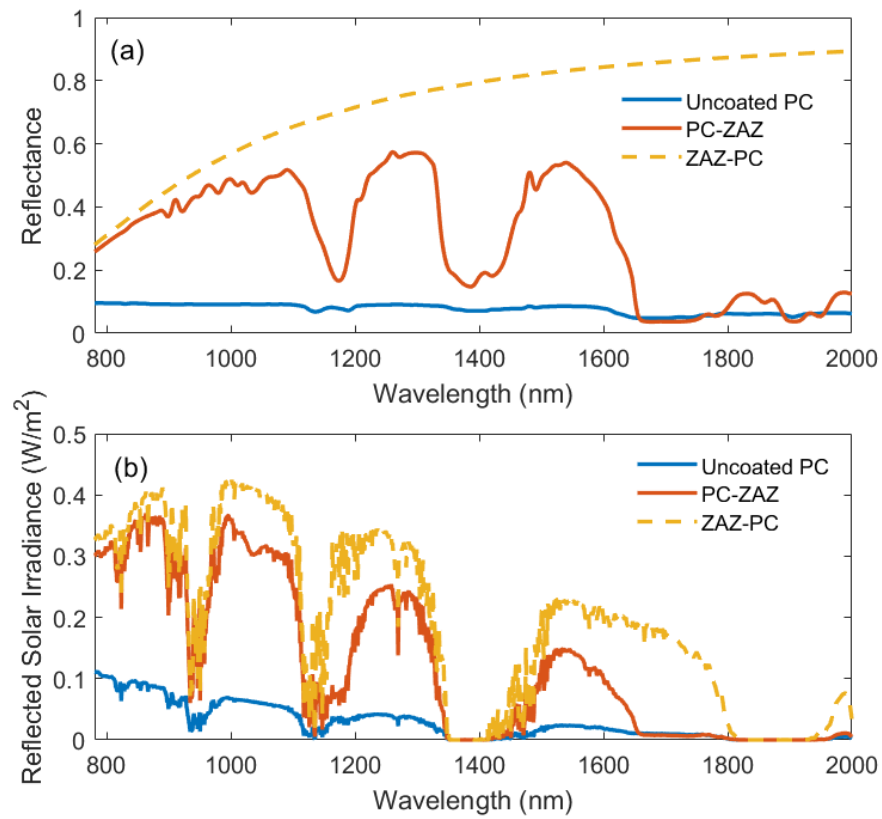


Figure 4.18. (a) Reflection spectra and (b) reflected solar irradiance as a function of the wavelength (780–2000 nm) for the PC and ZAZ-PC coatings. The top panel presents reflection percentage, while the bottom one shows reflected solar irradiance in W/m^2 .

Table 4.2. Average fraction of power transmitted, reflected, and absorbed through the structures of uncoated-PC, PC-ZAZ (coating at the interior side), and ZAZ-PC (coating at the exterior side) in the wavelength range of 780–2000 nm.

Structure	Average Fraction of Power in 780–2000 nm		
	Transmitted	Reflected	Absorbed
PC (without coating)	0.74	0.08	0.18
PC-ZAZ (Interior coating)	0.21	0.35	0.44
ZAZ-PC (Exterior coating)	0.21	0.69	0.10

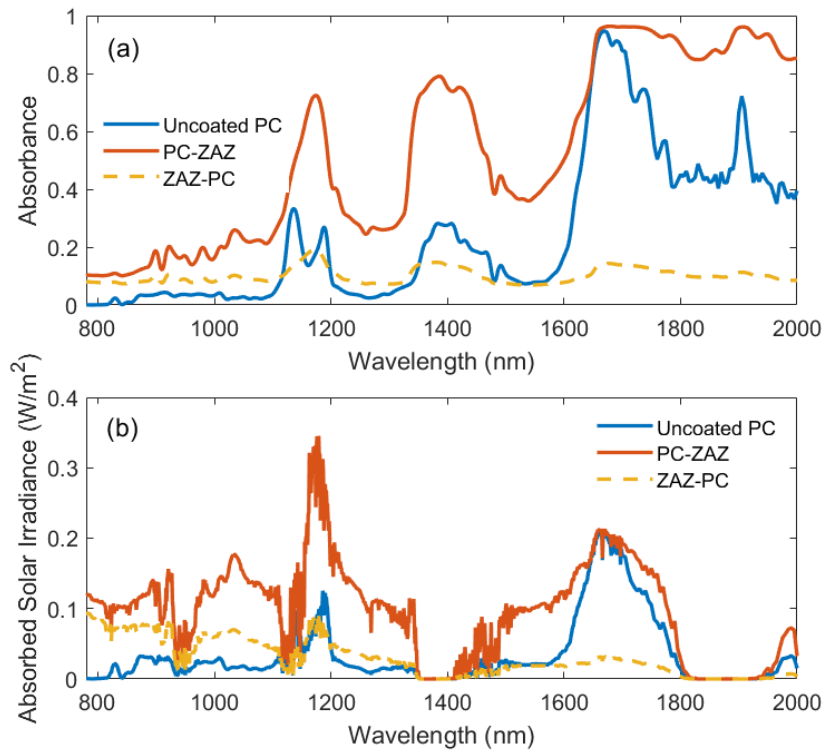


Figure 4.19. (a) Spectral absorbance and (b) solar irradiance absorbed through the PC, ZAZ-PC, and PC-ZAZ as a function of the wavelength (780–2000 nm). The top panel presents absorption percentage, while the bottom one shows reflected solar irradiance in W/m².

Table 4.3. Summary of total solar irradiance transmitted, reflected, and absorbed through the structures of uncoated-PC, PC-ZAZ (coating at the interior side), and ZAZ-PC (coating at the exterior side) in the wavelength range of 780–2000 nm.

Structure	Total Solar Irradiance (W/m ²) in 780–2000 nm		
	Transmitted	Reflected	Absorbed
PC (without coating)	315.81	33.62	33.59
PC-ZAZ (Interior coating)	135.22	152.57	95.23
ZAZ-PC (Exterior coating)	135.22	223.11	24.70

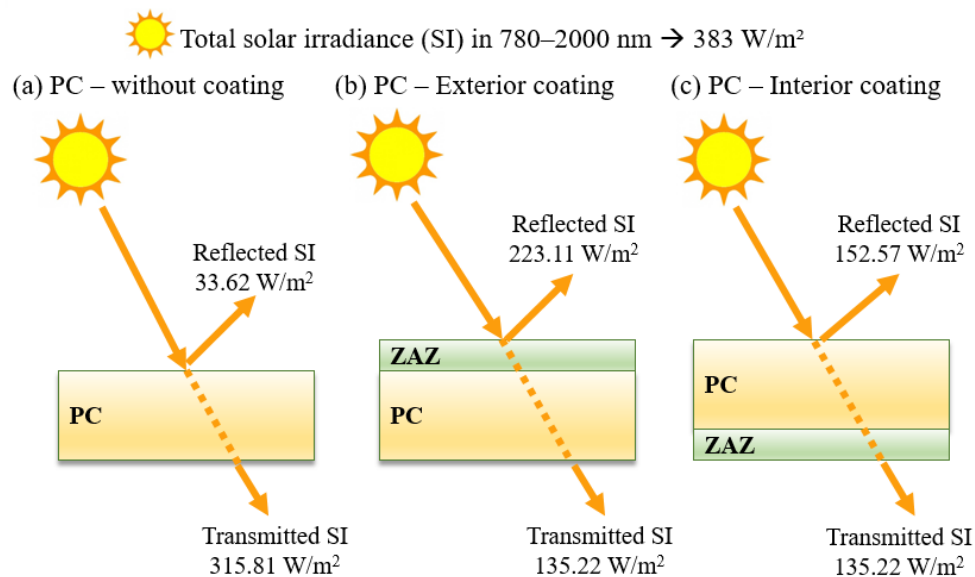


Figure 4.20. Illustration of the PC's response to solar irradiance (SI), both with and without the ZAZ coatings in the 780–2000 nm wavelength range. (a) PC without coating exhibits transmittance of 315.81 W/m², reflecting 33.62 W/m² of solar irradiation. (b) PC with an exterior ZAZ coating significantly increases SI reflectance to 223.11 W/m² and reduces transmitted SI to 135.22 W/m². (c) PC with an interior ZAZ coating achieves the same SI transmittance value of 135.22 W/m² and reflects 157.57 W/m² of the SI.

Since we know the SI transmitted through the ZAZ coated canopy, we can calculate the temperature increase of the cockpit. We developed an energy balance model as:

$$Q_{solar} = Q_{surfaces} + Q_{air} + Q_{re-emitted} + Q_{conducted} \quad (4.4)$$

where Q_{solar} is the total solar energy passing through the canopy, Q_{air} is the heat absorbed by the air, $Q_{surfaces}$ is the heat absorbed by the cockpit surfaces, $Q_{re-emitted}$ is the infrared radiation by surfaces, and $Q_{conducted}$ is the heat conducted through materials. In our model, the cockpit temperature does not change, and the air is assumed to be stationary within the cockpit; therefore, the airflow is ignored.

Then, we simplified our model by excluding the term $Q_{conducted}$, assuming that the components in the cockpit environment have good thermal insulation, which reduces the heat transfer. We also excluded the term $Q_{re-emitted}$, since Parson et al. proved that the re-radiation at longer wavelengths has a little effect on the temperature rise [115]. Then, our simplified model shrinks as follows:

$$Q_{solar} = Q_{surfaces} + Q_{air} \quad (4.5)$$

This model is based on the total solar energy passing through the canopy, Q_{solar} , is equal to sum of $Q_{surfaces}$ and Q_{air} absorbed by the air and the surfaces inside the cockpit, respectively. Q_{solar} is given by:

$$Q_{solar} = I_{Transmitted} \times A \times t \quad (4.6)$$

where $I_{Transmitted}$ is the transmitted solar irradiance and was calculated to be 135.22 W/m² for the PC with ZAZ coating. A is the area of the aviation transparent structure that is exposed to the solar irradiation and assumed 1 m², t is the exposure duration in s and for one hour it is 3,600 s. Using (4.6), we calculated Q_{solar} to be 487×10³ J. Similarly, Q_{solar} was calculated 1,137×10³ J for the PC without coating.

Q_{air} can be calculated by the following equation:

$$Q_{air} = m_{air} \times c_{p,air} \times \Delta T \quad (4.7)$$

where $c_{p,air}$ is the specific heat capacity of air and m_{air} is the mass of the air inside the cockpit and can be calculated as follows:

$$m_{air} = \rho_{air} \times V \quad (4.8)$$

where ρ_{air} is the air density and 1.184 kg/m³ at 25°C and 1 atm pressure, and V is the volume of the cockpit and taken to be 3 m³. m_{air} was calculated as 3.5 kg.

The specific heat capacity of air, denoted as $c_{p,air}$, is 1.0005 $\frac{J}{kgK}$.

$Q_{surfaces}$ can be computed by following equation:

$$Q_{surfaces} = m_{surfaces} \times c_{p,surfaces} \times \Delta T \quad (4.9)$$

where mass of the cockpit surfaces was assumed to be 50.0 kg and $c_{p,surfaces}$ is the specific heat capacity of surfaces, which was assumed to be 1500 $\frac{J}{kgK}$. Initial

ambient temperature of the cockpit is 25 °C (298 K). The temperature difference can be calculated by combining (4.5), (4.6), (4.7), and (4.9) as follows:

$$\Delta T = \frac{I_{Transmitted} \times A \times t}{m_{surfaces} \times c_{p,surfaces} + m_{air} \times c_{p,air}} \quad (4.10)$$

Solving (4.10), we calculated the temperature difference ΔT to be 6.18 K for the ZAZ-coated PC. Similarly, we calculated the temperature difference for the PC without ZAZ coating using (4.10). The solar irradiance passing through the PC without coating is 315.81 W/m², for which we calculated ΔT to be 14.41 K.

Next, we compared the heat capacity of the surfaces in the cockpit ($m_{surfaces} \times c_{p,surfaces}$) and the air ($m_{air} \times c_{p,air}$) to find their contribution to the heat build-up. Our findings show that the surface of the components in the cockpit absorbs the majority of heat from the transmitted solar irradiance, comprising 95.31% of

the overall heat accumulation. The air inside the cockpit absorbs 4.69%. Therefore, in thermal management, the design of the material's surface is crucial for maintaining comfort and safety during cockpit warming.

We find that the ZAZ-PC reflects solar irradiation, minimizing heat accumulation and preventing heat increase in the cockpit. Solar protection provides better temperature regulation inside the cockpit and a lower risk of equipment degradation over time. As a summary, if the PC and the ZAZ-coated PC canopies have a 1 m^2 area exposed to the solar irradiation and the volume of the cockpit is assumed to be 1 m^3 . We calculated the final temperature of the cockpit to be 39.41°C and 31.18°C for the PC and ZAZ-coated PC, respectively.

Our calculations demonstrate the significance of the coating in the context of solar protection and thermal comfort. Furthermore, we find it useful to mention that the thermal signature is also crucial as the objects heat up, they re-emit radiation at longer wavelengths in the mid- and far-infrared regions of the electromagnetic spectrum [116]. This re-emitted radiation can raise the thermal signature of the aircraft, making it more detectable by thermal radars and increasing its vulnerability against radars [117], [118].

4.4. Structural Characterization

In Section 4.4, we present structural characterization of the ZAZ-PC. The cross-section FESEM image of ZAZ-PC at room temperature, as shown in Figure 4.21a, confirms the thickness of the films was uniform. We determined the thickness of each layer as *ZTO top* (36 nm)/*Ag* (18 nm)/*ZTO bottom* (19 nm) – PC. The elemental distribution along the vertical path of the ZAZ layers was investigated using SIMS analysis, as shown in Figure 4.21b. Results analyzed by

Gaussian functions show maxima for Zn and Sn at the depths of 35 and 30 nm as well as 60 and 61 nm, respectively. The maximum of Ag occurs at 60 nm. Hence, heavier dopants penetrate a slightly shorter distance into the bottom layer, which is in good agreement with the literature [119]. The total thickness of the ZAZ structure lies around 72 nm. In addition, the thicknesses of the three layers were determined to be 20 nm (ZTO top), 18 nm (Ag) and 36 nm (ZTO bottom). Remarkably, these observations are in good agreement with the FESEM result. However, no sharp interfaces were detected between the layers. Moreover, for 50–69 nm, a significant Ag amount was detected. Thus, a metal ion-implanted diffusion effect is observable, also previously reported [120], [121].

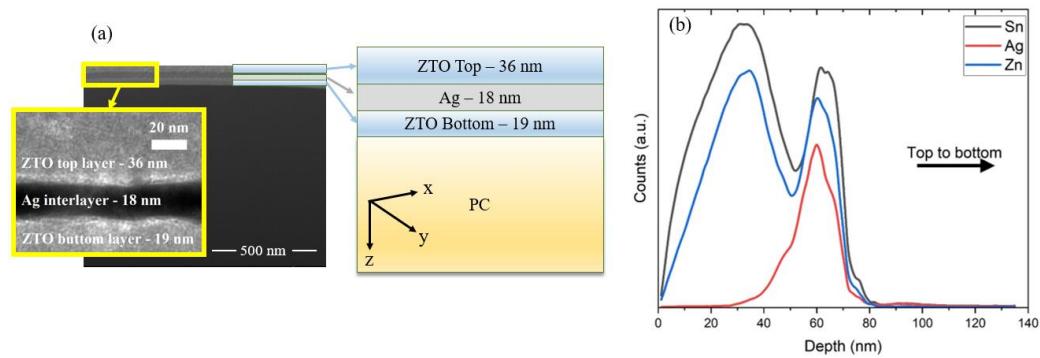


Figure 4.21. (a) Cross-sectional FIB image along with HRTEM inset and (b) SIMS analysis of the ZAZ–PC structure.

Before the ZAZ coating, the surface roughness of the uncoated PC was measured with AFM and 3D and 2D topographic images given in Figures 4.22a and b, respectively. The root mean square (RMS) value of the PC surface was found to be 0.64 ± 0.14 nm. Figures 4.23a, b, c and d show 2D and 3D AFM images of the different region of the ZAZ coated surface, where RMS surface roughness values were experimentally measured 1.79, 2.23, 1.38, and 1.48 nm, respectively. AFM results indicate a uniform texture and no visible defects. RMS surface roughness values indicate a relatively smooth surface compared to the coating thickness of ZTO and Ag layers.

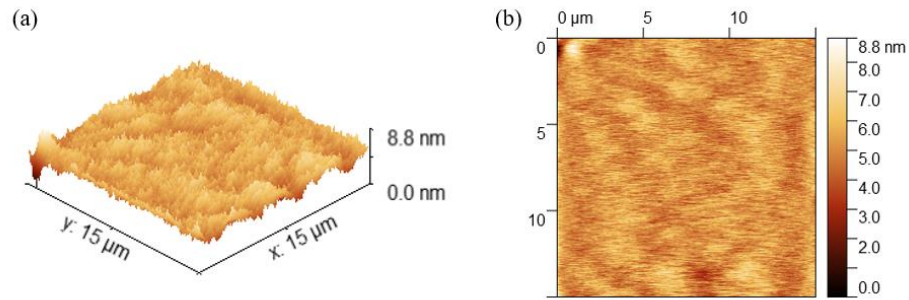


Figure 4.22. Representative (a) AFM 3D and (b) 2D topography images of the 5.8 mm thick PC substrate without thin-film coatings.

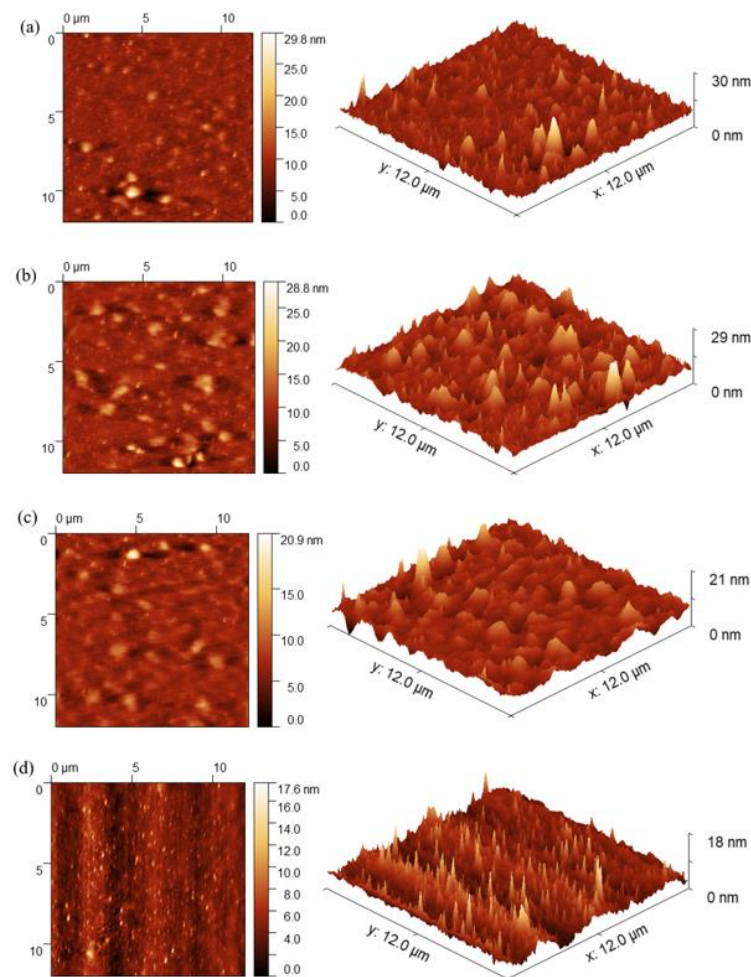


Figure 4.23. Representative AFM 2D and 3D topography images of different regions of the ZAZ-PC structure with RMS surface roughness values of (a) 1.79 nm, (b) 2.23 nm, (c) 1.38 nm, and (d) 1.48 nm.

AFM measurements can provide a sub-nanometer precision but limited to small areas [122]. Therefore, we used the laser scanning confocal microscopy to measure the surface roughness from an area of $140\ \mu\text{m} \times 1000\ \mu\text{m}$ according to the JIS B0601:2001 standard. The confocal microscopy results are found to exhibit an average surface roughness of 2 nm, aligning well with the AFM results, as shown in Figure 4.24.

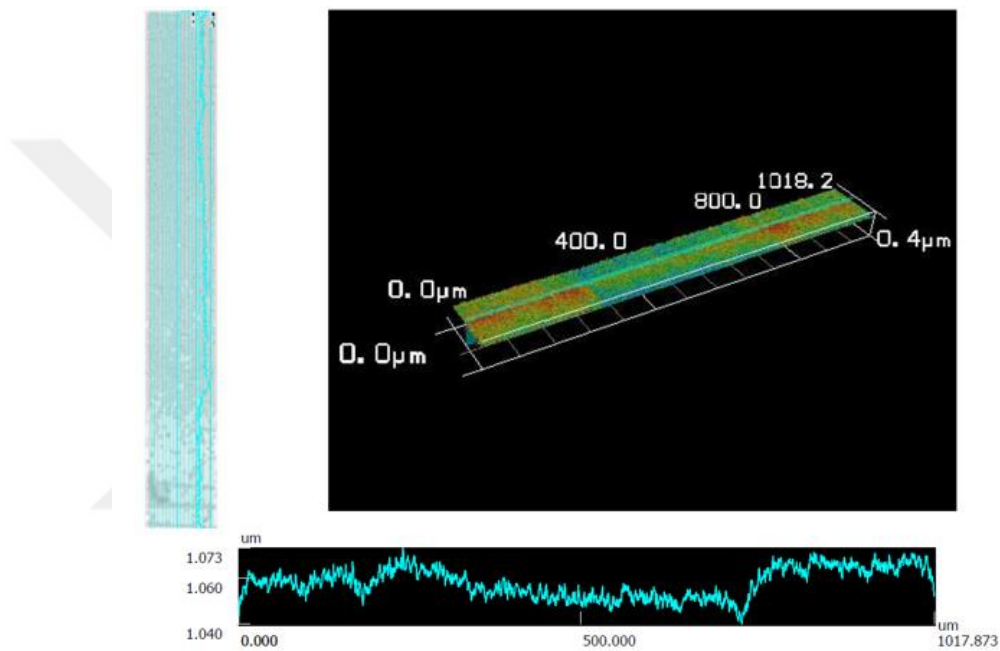


Figure 4.24. Surface roughness of the PC-ZAZ from an area of $140\ \mu\text{m} \times 1000\ \mu\text{m}$ according to the JIS B0601:2001 standard.

The X-ray diffraction (XRD) pattern of the fabricated ZAZ multilayers is presented in Figure 4.25. Figure 4.25 shows the GIXRD result of ZAZ film. It is shown that only partial crystallinity of ZTO is obtained with a very broad, amorphous peak at about 33.47° as previously reported in the literature [69]. The broad XRD peak is not sufficient for distinguishing the ZnSnO_3 and Zn_2SnO_4 phases. The peaks detected at 38.32° , 44.28° , and 64.79° belong to (111), (200), and (220), which were ascribed to the face centered cubic (fcc) structure of Ag, respectively (Ag JCPDS: 01-087-0719). The broadness of these peaks, likely due to the thinness of the layers, confirms the successful deposition of Ag between

the ZTO layers. Our findings demonstrate the potential of the optically transparent EMI shielding material to provide effective shielding while maintaining a smooth and visually appealing surface for transparent EMI applications, shown in Figure 4.26.

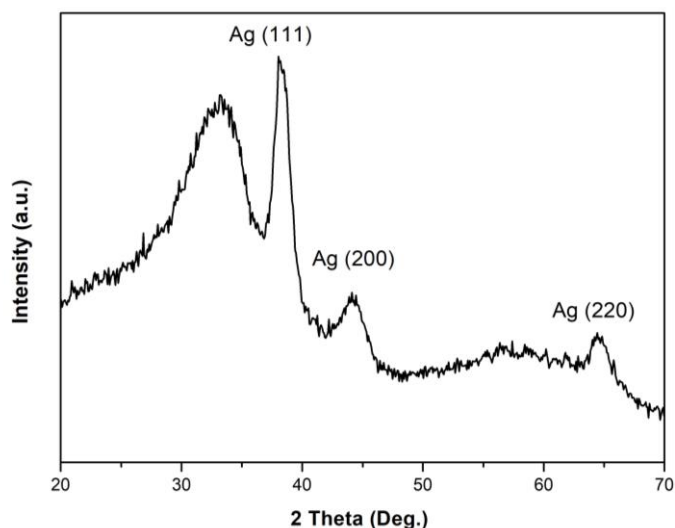


Figure 4.25. GIXRD result of the ZAZ film on PC substrate.

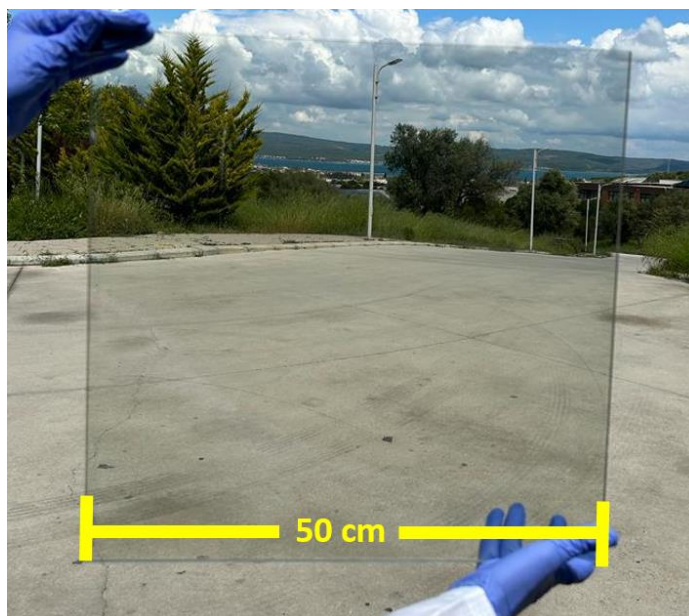


Figure 4.26. Photo image of a 50 cm × 50 cm optically transparent EMI shielding of PC-ZAZ.

4.5. Summary

In Chapter 4, we expand the study of EMI shielding performance to cover the optical performance, including solar radiation protection, optical clarity, and night-vision applications, which present contradicting requirements. We realized an optically transparent EMI shield utilizing ZAZ stratified films on PC over a large area of 50 cm $\times$ 50 cm. The optical and electromagnetic properties of the structure were validated thoroughly by numerical and experimental results. The ZAZ structure has a sheet resistance value of 10 Ω /sq, optical loss of 13% in the visible region, and shielding effectiveness of 27 dB across the 2–20 GHz frequency range.

Moreover, we discussed the effect of ZAZ coating on solar irradiation and its impact on the thermal signature. Our calculations show that the ZAZ coating can block solar radiation up to 135.22 W/m², reducing solar radiation by 57.2%. To further enhance the effectiveness of solar protection, thin films with lower sheet resistance are necessary. However, a decrease in the sheet resistance also reduces optical transmission in the visible spectrum, potentially compromising the pilot's visibility. Additionally, thin films with lower sheet resistance can negatively impact the transmittance needed for night-vision systems, further compromising performance in low-light conditions. The optical response in the near-infrared region can be adjusted through ZTO film thickness (particularly with the top one) while keeping its EMI properties unchanged. In addition, a structural analysis of the ZAZ–PC structure was performed to examine the surface roughness and depth profile. Besides EMI shielding, the ZAZ–PC structure with low RMS value, high electrical conductivity and large optical transmission might be a promising candidate for other large-area optoelectronic applications.

Chapter 5

Three-Dimensional Optical Performance Analysis of Aviation Transparencies

Chapter 5 includes the optical performance analysis of three-dimensional (3D) canopies made of optically transparent polymers and their thin-film coating counterparts. In Chapter 4, we used the transfer matrix method to analytically calculate the optical characteristics of the two-dimensional structures as a function of the wavelength. Here, we proposed a method to evaluate the optical performance of the 3D canopy transparency, specifically the angular deviation and optical transmittance, using ray optics.

The material's optical constants and geometry determine the optical transmission, reflection, refraction, absorption, or transmission of rays. These interactions can result in a decrease in the optical performance of the structures, including optical distortion and clarity [123]. The optical distortion is the difference between the actual direction of a ray and its expected direction. Due to the optical distortion, pilots or passengers can see the objects distorted. Particularly for pilots, this distorted view can pose significant challenges, necessitating the elimination of

this design element [124]. On the other hand, the optical clarity is another crucial parameter, indicating the extent of light transmission through the structure. Structures with poor optical clarity may not allow pilots to maintain visibility when the illumination of the outside is minimal [125].

Both optical distortion and clarity influence the pilot's vision through the canopies or windshields, thereby facilitating accurate view of the outside and enhancing flight safety [126], [127]. Since clear pilot vision is crucial in aviation, it is important to consider optical performance when designing transparent parts of air vehicles such as windshields and canopies.

We performed ray optics analysis on the 3D canopies using the COMSOL Multiphysics ray optics module and TracePro to analyze the effect of geometry and materials. In ray optics module, keeps track of the optical flux associated with each ray as the rays propagate along the thin-film-coated canopy transparency model at a given wavelength. We can trace rays and ray flux time-dependently to compute optical transmittance by using:

$$T = \frac{P_T}{P_I} \quad (5.1)$$

where T is transmittance defined as the ratio of transmitted power, P_T to incident power P_I of the ray.

We assessed the optical distortion across the canopy transparency using the coordinates of each ray, in addition to the optical transmittance. We designated the 3-dimensional ray vectors before and after interaction with the canopy transparency as vector A and vector B , respectively, where:

$$A = (x_1, y_1, z_1) \quad (5.2)$$

$$B = (x_2, y_2, z_2) \quad (5.3)$$

Next, we calculate the angular deviation (θ), utilizing the angle between vector A and vector B for each ray as follows:

$$\theta = \cos^{-1} \left(\frac{x_1 x_2 + y_1 y_2 + z_1 z_2}{\sqrt{x_1^2 + y_1^2 + z_1^2} \cdot \sqrt{x_2^2 + y_2^2 + z_2^2}} \right) \quad (5.4)$$

Figure 5.1 represents the test setup specified by the ASTM standard F733-19 to determine the optical deviation of the canopy. In our analysis, we placed a control screen to determine the coordinates of the rays impinging on it and then calculated the optical transmittance and deviation using (5.1) and (5.4), respectively.

As discussed in Chapter 4, we selected the ZTO/Ag/ZTO sandwich architecture as our thin-film coating. We obtained the optical constants of PC, stretched PMMA, Ag, and ZTO layers using the VASE Ellipsometer – J.A. Woollam, USA, as given in Table 5.1, were used in the ray optics analysis. Based on the thin-film interference theory, the ZAZ-coating with a total thickness of 78 nm introduces a negligible effect on the angular deviation due to its very small optical path difference compared to the thickness of canopy transparencies [128].

Even though the refractive indices of the ZAZ-coating are different from that of the canopy transparency material, this small optical length difference cannot alter the angular deviation. However, the ZAZ-coating can alter the transmittance of the canopy transparency to be applied due to the high extinction coefficient. For this reason, we did not include the ZAZ-coating in our angular deviation calculation in Section 5.1, but included in Section 5.2 for the optical clarity calculations.

Table 5.1. Refractive indices (n) and extinction coefficients (k) of PMMA, PC, ZTO and Ag at the wavelengths (λ) of 550 nm and 700 nm.

	PC		PMMA		ZTO		Ag	
λ (nm)	n	k	n	k	n	k	n	k
550	1.59	6.72×10^{-7}	1.49	4.73×10^{-8}	1.90	0.04	0.64	3.15
700	1.57	9.82×10^{-8}	1.48	6.07×10^{-8}	1.86	0.03	0.15	3.68

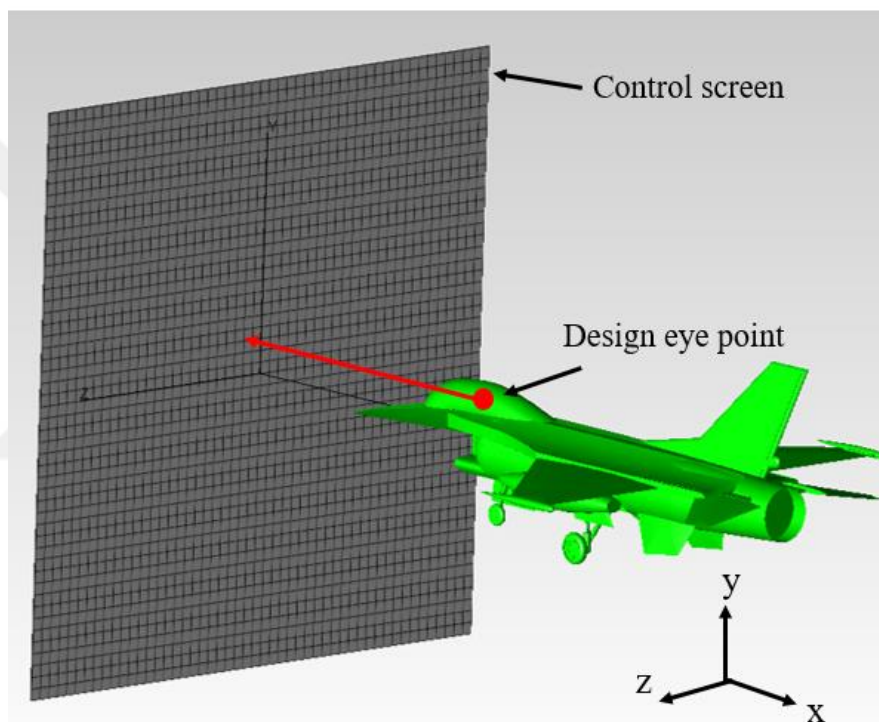


Figure 5.1. Representative model of the canopy with a ray source (shown in red dot) positioned at the design eye point. We use the control screen to determine the coordinates of the rays.

The solid model of the canopy transparency and its meshed version used in the numerical calculations are shown in Figures 5.2a and b, respectively. A spherical light source with 150,000 rays was placed in a possible pilot position, design eye point (DEP), as specified by the ASTM standard F733-19, shown with a red dot in Figure 5.2c. The 2D schematic of the ZAZ-coated canopy structure, composed of ZTO layers and an Ag layer, is illustrated in Figure 5.2d.

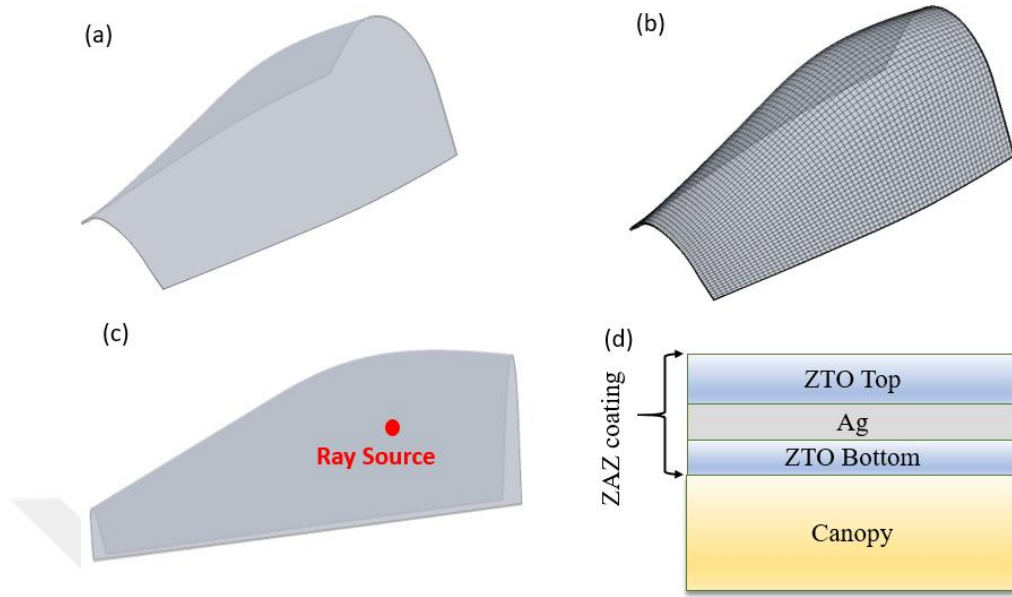


Figure 5.2. Solid model of the (a) the 3D canopy transparency and (b) its meshed version. (c) Side-view of the canopy transparency with a ray source shown in red, positioned at the design eye point. (d) 2D architecture of a thin-film-coated canopy made of optically transparent polymers such as PMMA or PC. The thin-film coating consists of ZTO Top /Ag/ZTO Bottom.

5.1. Angular Deviation Analysis

In this section, we conducted a ray optics analysis to calculate the angular deviation using (5.4). We mapped the angular deviation onto the PC canopies with thickness values of 10, 20, and 30 mm at a wavelength of 550 nm, as shown in Figures 5.3a, b, and c, respectively. The colorbar indicates the level of angular deviation, with red representing the highest level, resulting in a more distorted view. The level of angular deviation decreases from red to blue, in which one can see a less distorted view compared to the red-colored ones.

Similarly, we calculated angular deviation for the PMMA canopies with thickness values of 10, 20 and 30 mm for comparison purposes, as shown in Figures 5.4a, b, and c, respectively. We summarized the minimum and maximum

angular deviation (in mRads) of PC and PMMA with thicknesses of 10 mm, 20 mm, and 30 mm at the wavelengths of 550 and 700 nm in Tables 5.2 and 5.3, respectively.

Our ray optics analysis shows that the thinner samples yield lower angular deviations. The angular deviation increases as the canopy transparency grows thicker. This increase in the ray deviation is due to the longer optical paths [129]. We calculated the angular deviations ranging from 1.25×10^{-2} to 5.72 mRads for 10 mm PC and from 1.11×10^{-2} to 5.72 mRads for 10 mm PMMA. There is no difference between 10 mm PC and PMMA in terms of their angular deviation due to the small difference in their refractive indices. To observe the difference between these two similar but not identical materials in terms of refractive index, longer paths are needed.

As the thickness increases, the PC has a higher angular deviation than the PMMA counterparts. We calculated the angular deviation range of 20 mm PC from 2.50×10^{-2} to 11.40 mRads and 2.23×10^{-2} to 11.20 mRads for 20 mm PMMA. Further, increasing the thickness of the canopy transparency to 30 mm causes an angular deviation of 17.30 mRads for PC and 16.90 mRads for PMMA. This higher level of deviation is due to the higher refractive index value of PC compared to PMMA at the given wavelength of 550 nm. High-refractive-index materials bend incoming rays more, leading to a higher angular deviation [130]. Thus, PC has a higher angular deviation than the PMMA because of its higher refractive index at the given wavelength.

The top part of the canopy transparency for both PMMA and PC has the lowest value of angular deviation since the ray impinges on the surface at an angle close to normal. Jiang et al. showed how an incident angle close to the surface normal minimizes angular scattering by tailoring the materials and geometry [131]. The angular deviation increases from the top to the edge along the canopy, regardless

of thickness, due to the increasing angle between the rays and the surface normal. As the angle of incidence shifts away from the surface normal, particularly toward the edges of the canopy transparency, the quality of the view from the DEP deteriorates.

We observed similar results for the angular deviation in the ray optics analysis at a wavelength of 700 nm. This similarity in angular deviation at the wavelengths of 550 and 700 nm is due to the materials having refractive indices of 1.59 and 1.57 for PC and 1.48 and 1.49 for PMMA.

We found that the distorted view is primarily due to the angular deviation of both PMMA and PC, which strongly depend on the thickness rather than the refractive index. Besides, our analysis shows that the difference between PMMA and PC extinction coefficients does not affect the angular deviation since it is mainly related to absorption rather than rays' optical paths [132].

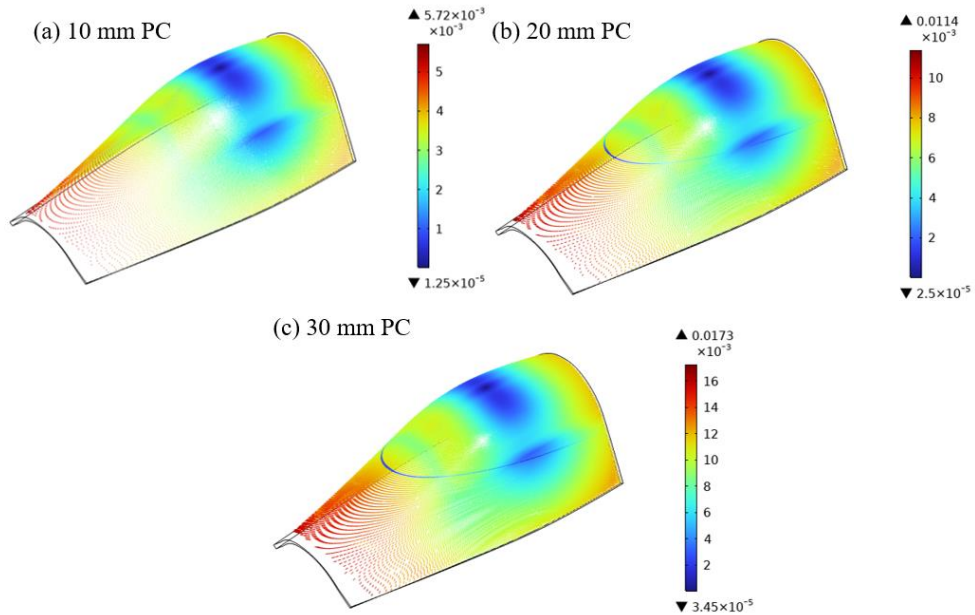


Figure 5.3. Angular deviation (in radians) mapping of the (a) 10 mm, (b) 20 mm and (c) 30 mm uncoated PC at the wavelength of 550 nm with perspective view.

Table 5.2. Minimum and maximum values of angular deviation (in mRad) of 10, 20, and 30 mm PC at the wavelength (λ) of 550 and 700 nm.

λ , nm	PC					
	10 mm		20 mm		30 mm	
	θ_{min} (mRad)	θ_{max} (mRad)	θ_{min} (mRad)	θ_{max} (mRad)	θ_{min} (mRad)	θ_{max} (mRad)
550	1.25×10^{-2}	5.72	2.50×10^{-2}	11.40	3.45×10^{-2}	17.30
700	1.27×10^{-2}	5.71	2.53×10^{-2}	11.40	3.50×10^{-2}	17.30

Table 5.3. Minimum and maximum values of angular deviation (in mRad) of 10, 20, and 30 mm PMMA at the wavelength (λ) 550 and 700 nm.

λ , nm	PMMA					
	10 mm		20 mm		30 mm	
	θ_{min} (mRad)	θ_{max} (mRad)	θ_{min} (mRad)	θ_{max} (mRad)	θ_{min} (mRad)	θ_{max} (mRad)
550	1.11×10^{-2}	5.72	2.23×10^{-2}	11.20	3.09×10^{-2}	16.90
700	1.12×10^{-2}	5.72	2.25×10^{-2}	11.20	3.12×10^{-2}	16.90

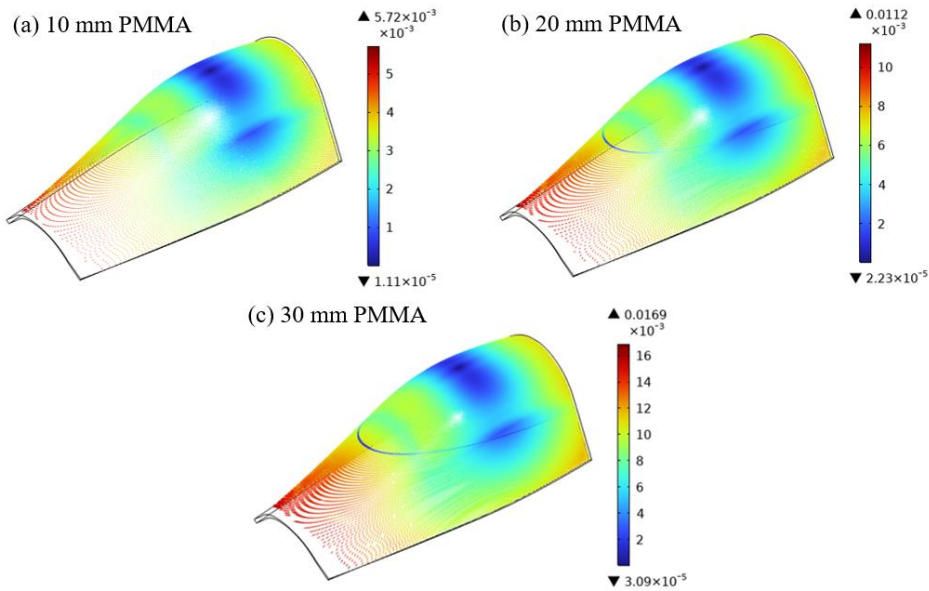


Figure 5.4. Angular deviation (in Rad) mapping of the (a) 10, (b) 20 and (c) 30 mm uncoated PMMA at the wavelength of 550 nm with perspective view.

5.2. Optical Transmittance Analysis

In this section, we expanded our angular deviation calculations to optical clarity for complete optical performance evaluation. To this extent, we calculated the optical transmittance of PC and PMMA at 550 nm using ray optics. Since the visible region lies between 400-700 nm, we selected the wavelength of 550 nm, the mid-wavelength of which the human eye is most sensitive [133], for our calculations.

We calculated the optical transmittance mapping using (5.4) for the 10 mm, 20 mm, and 30 mm thick PC canopies, as shown in Figures 5.5a, b, and c. Similarly, Figures 5.6a, b, and c present the optical transmittance of PMMA for 10 mm, 20 mm, and 30 mm, respectively. We determined the minimum and maximum transmittance values of PMMA and PC with thicknesses of 10 mm, 20 mm, and 30 mm at the wavelength of 550, which were summarized in Table 5.4. For the 10-mm PC canopy, the calculated optical transmittance ranges from 0.25 to 0.76 and 0.31 to 0.92 for the PMMA canopy.

However, as the thickness increases to 20 and 30 mm, the maximum transmittance decreases to 0.72 and 0.69, respectively, while the minimum transmittance reduces to 0.15 and 0.08 for the PC canopy. The maximum transmittance of the PMMA ones is 0.91 and 0.90, while the minimum transmittance values are 0.23 and 0.14, respectively. According to Table 5.1, PMMA exhibits a higher optical transmittance than PC because it has a lower extinction coefficient and refractive index at the given wavelength. The refractive index value close to the air ($n = 1$) reduces the reflection of the rays, resulting in a more significant portion of them transmitting through the canopy transparency. Furthermore, the lower extinction coefficient enhances transmittance by reducing the amount of absorption through the canopy.

The optical transmittance for the PC and PMMA canopies exhibit significant variation across their surface. Both canopies yield higher transmittance concentrated near the center and top parts and lower transmittance through the edges. This behavior is due to the geometric effects, which lead to ray refraction and a higher extinction coefficient in thicker samples due to increased path lengths and scattering, causing this non-uniformity [134].

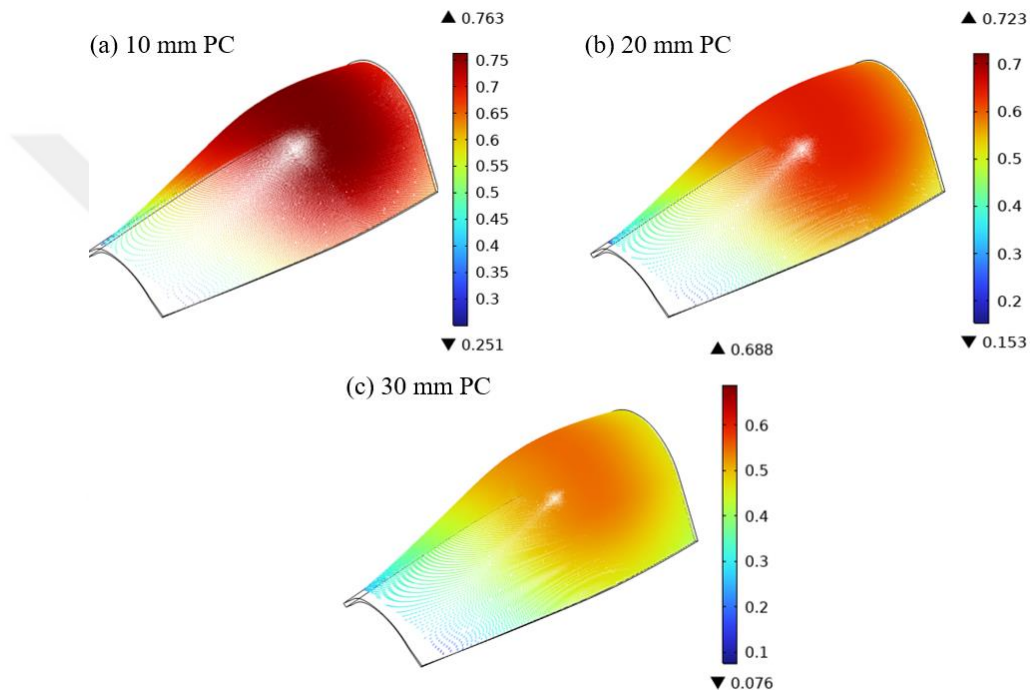


Figure 5.5. Optical transmittance mapping of the 10 mm (a), 20 mm (b) and 30 mm (c) PC at the wavelength of 550 nm with perspective.

Table 5.4. Minimum and maximum values of optical transmittance of 10 mm, 20 mm, and 30 mm uncoated PMMA and uncoated PC at the wavelength (λ) of 550 nm.

	Maximum and minimum values of optical transmittance at 550 nm					
	10 mm		20 mm		30 mm	
	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}
PC	0.25	0.76	0.15	0.72	0.08	0.69
PMMA	0.31	0.92	0.23	0.91	0.14	0.90

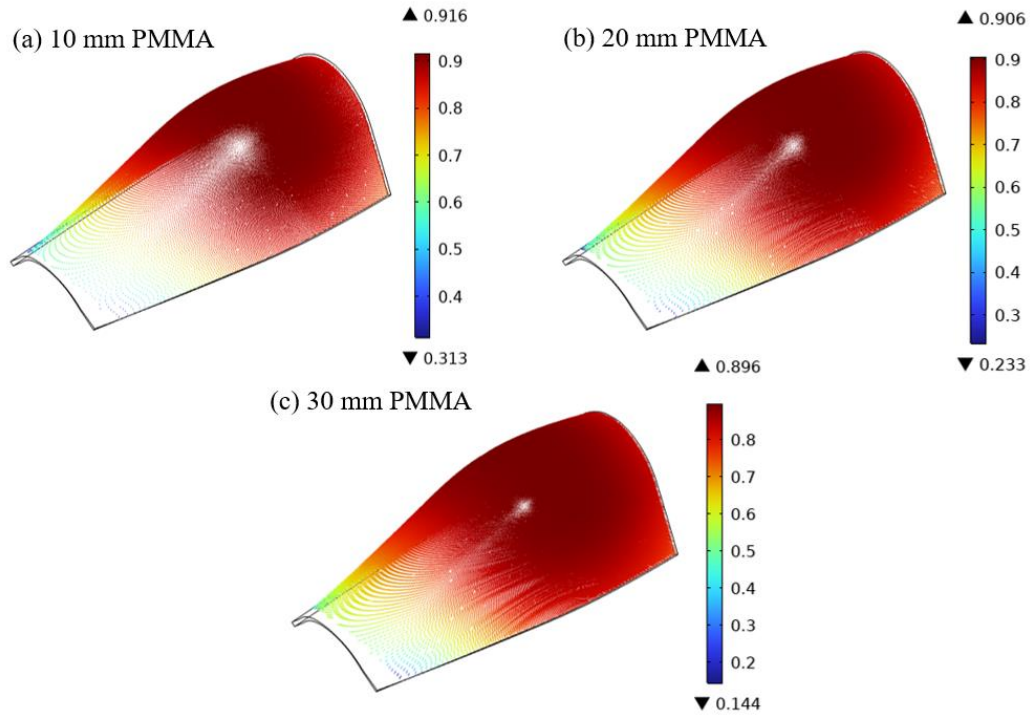


Figure 5.6. Optical transmittance mapping of the 10 mm (a), 20 mm (b) and 30 mm (c) PMMA at the wavelength of 550 nm with perspective.

Next, we calculated the effect of ZAZ-coating on transmittance at 550 nm for the PC and PMMA canopies, as shown in Figures 5.7 and 5.8, respectively. We applied the determined ZAZ-coating thicknesses from Chapter 4 to the 3D canopy transparency model for the ray optics analysis. We present optical transmittance mapping of 10, 20 and 30 mm for the PC and canopies, as shown in Figures 5.7a, b, and c, respectively. The optical loss in the maximum transmittance is 0.18, 0.23, and 0.27 for 10, 20, and 30 mm PC canopies at 550 nm. The increase in optical loss as the thickness increases is attributed to the higher extinction coefficient of the PC, as the ZAZ coating contributes to the same extent for all canopies.

We mapped the calculated optical transmittance at 550 nm for 10 mm, 20 mm, and 30 mm PMMA canopies, as shown in Figures 5.8a, b, and c, respectively. We found the optical loss due to the ZAZ coating to be 0.23 for all thickness

values. This difference in the optical loss of PC and PMMA is due to the superior optical constant of PMMA. Table 5.5 summarizes the minimum and maximum transmittance values of ZAZ-coated PMMA and PC at the wavelength of 550 nm, with thicknesses of 10 mm, 20 mm, and 30 mm, respectively. We observed the minimum transmittance values along the edges of the canopies due to the higher level of refraction and reflection compared to the top side of the canopy transparency, which shows similar behavior to the uncoated canopies.

Table 5.5. Minimum and maximum values of numerically calculated optical transmittance of ZAZ-PC at the wavelength (λ) of 550 nm with thicknesses of 10 mm, 20 mm, and 30 mm.

	Maximum and minimum values of optical transmittance at 550 nm					
	10 mm		20 mm		30 mm	
	T_{min}	T_{max}	T_{min}	T_{max}	T_{min}	T_{max}
ZAZ-PC	0.07	0.58	0.07	0.49	0.07	0.42
ZAZ-PMMA	0.07	0.69	0.07	0.68	0.07	0.67

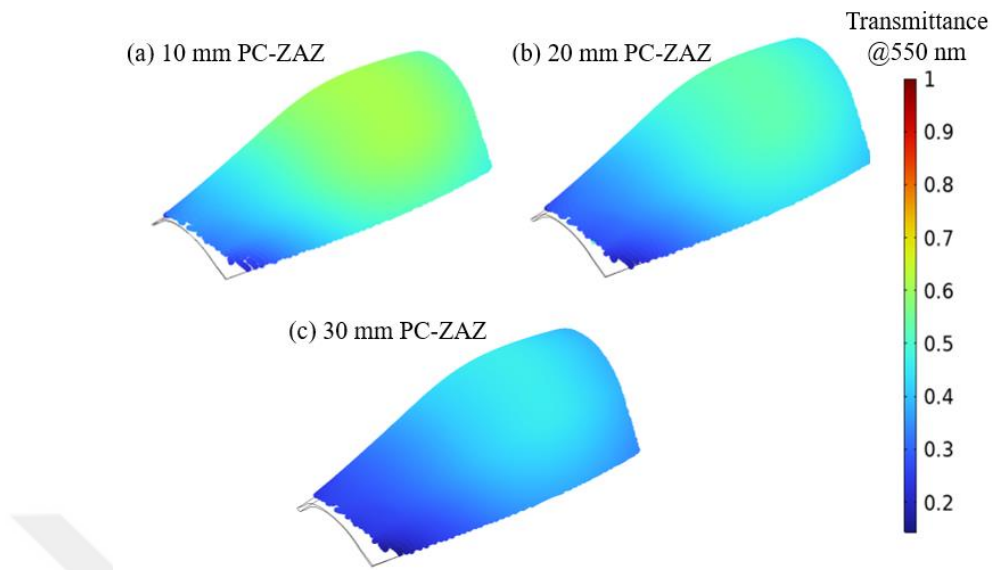


Figure 5.7. Numerically calculated optical transmittance at 550 nm for ZAZ-coated PC with a thickness of (a) 10 mm, (b) 20 mm, and (c) 30 mm.

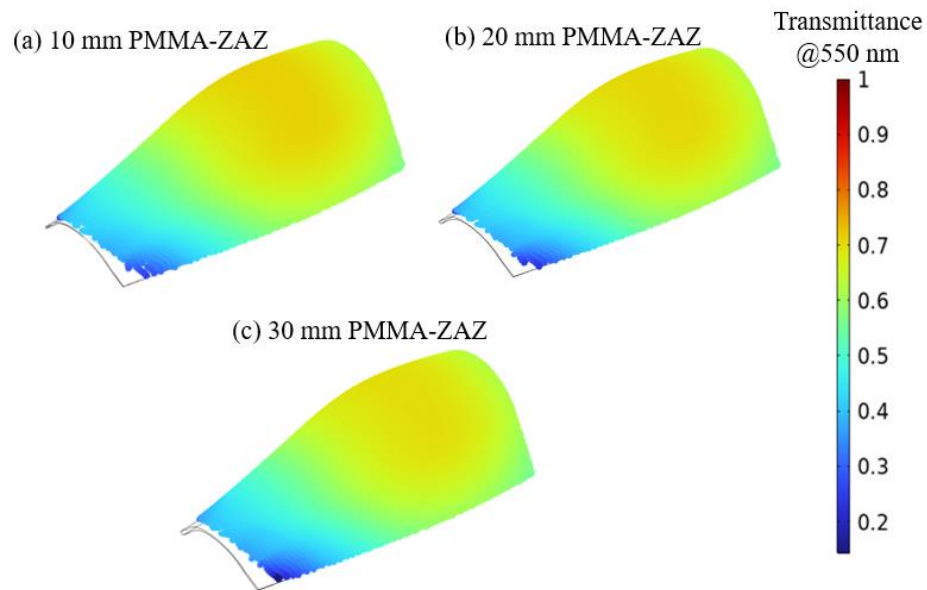


Figure 5.8. Numerically calculated optical transmittance at 550 nm for ZAZ-coated PMMA with a thickness of (a) 10 mm, (b) 20 mm, and (c) 30 mm.

5.3. Summary

In this chapter, we studied the optical performance of large-scale canopies made of PC and PMMA and their thin-film-coated (i.e., ZTO/Ag/ZTO, ZAZ) ones at the wavelength of 550 nm. The ZAZ-PMMA offers superior optical properties compared to the ZAZ-PC. In addition to the higher optical quality of stretched PMMA, they resist scratches but cannot withstand mechanical impact as PC can [135], [136]. Therefore, in modern aviation, canopy transparencies are designed to combine superior properties of PMMA and PC through lamination [137].

The materials with higher optical loss, such as PC and Ag, significantly decrease the optical transmittance as their thickness increases. In contrast, materials with lower extinction coefficients, such as PMMA and ZTO, do not reduce the transmittance. The ray tracing analysis proposed here is applicable to three-dimensional large-scale geometries. Still, it is limited to a single wavelength and unsuitable to compute layers with sub-wavelength thickness [138]. We suggest both ray tracing and TMM (as discussed in Chapter 4) methods for the complete optical design of a transparent structure.

The optical transmittance is critical for pilots since it directly affects the clarity of their view through the canopy transparency. Besides, the angular deviation can make the view appear distorted and affect the pilot's ability to see the image as closer or farther away, especially for thick and highly curved structures. As clear pilot vision is crucial in aviation, optical performance must be considered when designing transparent parts of air vehicles, such as windshields, windows, and canopies. We can apply our proposed methodology to any transparency and thin-film coating counterparts to assess the viewing area's optical performance.

Chapter 6

Conclusion

6.1. Contributions to Scientific Knowledge and Industry

In this thesis, we have investigated optical and electromagnetic properties in transparent aviation structures and their thin-film-coated versions. To this end, we have designed and realized large-area thin-film coatings to overcome practical challenges in coating free-form objects, which is impossible with conventional coating systems. By realizing the large-area thin-film coating, we were able to test the structure's ability to block electromagnetic interference over a wide spectral range.

Particular challenges we have addressed in this thesis encompass poor optical and electrical performance of the thin-film-coated structure due to the non-uniformity of the film. We solved this issue by optimizing the coating parameters and determining the optical response of each layer, thereby engineered both

transparency and conductivity in a controlled manner. In the thin-film-sandwiched structure, the thickness of the metal layer primarily influences the sheet resistance and exhibits minimal tolerance during the coating process. The large-area coating of the metal layer dramatically decreases the optical transmission, which requires low tolerance values, whereas the oxide layers slightly affect it. The decrease in optical transmission is due to the lower sheet resistance values, which increase the electromagnetic interference shielding performance. Therefore, the trade-off between the optical and electrical properties of the structure has been restraining the potential of high-quality optoelectronics. Our study provides a deeper understanding of this trade-off, which suggests ways to mitigate it, such as employing multilayer stacks to sustain high EMI shielding with minimum optical loss.

We presented a large-area coating system and investigated electrical, optical, and structural characterization of the large-area thin-film-coating. This integrated characterization framework allowed us to correlate structural properties with the structure's electrical and optical ones, enabling the development of a more reliable and repeatable fabrication approach. Our combined study aims at covering free-form objects with electromagnetic interference shielding that is optically clear. This covers the widest range that has been reported so far. This makes large-area thin film coatings exciting for the aviation industry. Furthermore, we studied solar irradiation protection thanks to the reflective feature of the thin-film coating, which offers power saving for air-conditioning systems.

We also introduced a methodology to evaluate the optical performance of three-dimensional canopies. This methodology utilizes ray optics and enables the determination of optical distortion and transmittance at large scales, such as canopies and windshields of air vehicles. We believe that our proposed method is helpful for aircraft designers and engineers, enabling them to accurately predict visual fidelity and safety metrics in the early-stage designs.

Overall, the findings of this thesis advance the current understanding of electromagnetic interference shielding and low observability features, considering the trade-off with optical performance. Our approach covers materials selection, large-scale fabrication, and electrical and optical performance trade-offs and establishes a base that can spur the next generation of aerospace innovations and beyond. Furthermore, we believe these findings will help the civil and military use of transparent conductive materials for large-scale applications and enhance aircraft stealth capabilities, passenger comfort, and operational efficiency.

6.2. Challenges and Future Outlook

The large-area thin-film coating system and design methodologies presented in this thesis are suitable for various materials. Integrating an additional degree of freedom into the system enables free-form curved and planar objects to be coated. This modification suggests coating optically transparent films at nanometers for large-scale curved transparencies, but it can also apply to nontransparent components. Furthermore, transforming a planar surface into a patterned form, known as a metasurface, improves its performance.

These metasurface structures are available at lab scales; however, when it comes to the industry, due to the limitations of coating and patterning systems, they are not widely used, even if they are needed. Besides, challenges in analyzing metasurface-integrated large-area complex geometries become more pronounced. These issues underscore the importance of ongoing research in advanced patterning, scalable manufacturing, and systems-level design (i.e., radar cross-section analysis) to harness the advantages of metasurfaces fully. These needs increase, especially in military applications, with the advancement in tracking and detection systems. Therefore, the techniques and strategies outlined in this thesis will continue to progress.

The primary difficulty in achieving large-area coating on free-form objects is ensuring uniform coating and establishing thickness tolerances for the coating system. This approach is cost-effective because it requires a low tolerance for the metal, while the metal oxide layer does not require as sensitive a coating. Our design approach for microwave and visible regions will serve as a guide, depending on the specific application with only one metal or metal oxide layer.

Another future focus of this study is to provide long-term durability and resistance against environmental conditions. We can incorporate an optically transparent protective layer into our design for enduring environmental conditions such as UV exposure, fog and salt, mechanical wear, and stress. This protective layer does not necessitate any electrical properties to meet its electromagnetic performance requirements, such as electromagnetic interference shielding or low-observability features. Yet, it might be helpful to include this protective layer in the design procedure and analyze the trade-off between its optical and electrical properties. Integrating a protective layer increases the service life and meets the safety requirements.

Finally, potential synergy exists with the electromagnetic features of EMI shielding, LO, and energy-efficient technologies through solar irradiation protection. Future coating systems could incorporate dynamically adjustable layers or adaptive materials to respond to varying optical, electromagnetic or thermal settings in real-time, hence providing multi-functional performance. In sum, the fabrication process and optoelectrical design methodologies presented here establish the potential of surface modification with thin-film coatings that can be applied to aviation and other civil applications.

6.3. Publications and Patents

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